TECHNOLOGY OVERVIEW BEFORE TOKEN/NETWORK:

SUPER PRE BETA DRAFT WORK IN PROGRESS DESCRIPTION OF THE PROPRIETARY ALGORITHM. TBD MEANS: "I KNOW, BUT CAN'T TELL YOU YET."

DISCUSSION: HTTPS://DISCORD.GG/GVYFNKU

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COMPUTER MODELLING MUST BRING US INTO THE FUTURE!

- Most of mankind's greatest achievements were modeled in a computer before we could make them in the real world. Computer modeling is key to the revolution that will bring mankind into the future we've been promised in science fiction.
- Nuclear Fusion
  - Limitless free energy from nuclear fusion will only be possible through modelling plasma fusion containment geometries.
- Traditional power generation
  - Oil and gas, where is the best spot to drill? How deep? Reactor vessels, cooling towers, steam turbines.
- Rockets
  - Those rockets that will be taking us to mars; they don't get built until they're modelled in the computer first. The fuel cryostorage, the reactor, the nozzles, the descent flaps, all get modelled in computer first.
- Space travel
  - Even the space suit needs modelling due to the pressure differential of space's vacuum.
- Aeronautical
  - More efficient aircraft that get passengers where they want to go, faster, and at greater fuel savings.
- Nautical
  - More efficient hull geometries, skin texture, sail geometry, propeller geometry. The bubbles tankers blow underwater to reduce water friction, and the cylindrical wind turbines for power deck side.

COMPUTER MODELLING MUST BRING US INTO THE FUTURE!

- Biotech
  - Artificial hearts, joint replacements, Breathing machines, and nanobots all must be modelled for efficacy and safety before the first prototype is built.
- Drones
  - Better rotor geometries, more aerodynamic hull structure, foul weather optimization, vastly easier in the computer than in prototyping.
- Extinction level events
  - How can we prevent Yellowstone from bowing it's top off and causing an ice age? How will the volcano react to different interventions such as cooling, or gradual pressure release?
- Global warming
  - How much of it is caused by humans, were we already headed for an ice age or a greenhouse? What interventions can have the greatest impact at the lowest cost.
- Natural disasters
  - Storms have been more powerful recently than in recorded history. What affect this new activity have on rainfall patterns, and crop growth?
- Basically, if you want to make anything in the real world that has air, water, steam, gas, aerosols, droplets or plasmas flowing around or through it, you need to model it in the computer first, before you spend tons of money building it.
- Now that you know how vital computer modelling is to mankind's progress, see the problems engineers and scientists face today.
- You've heard of super computers right? Well, super computers exist, for the most part, to perform exactly that. The giant rows of computers full of blinking lights are working right now, trying to find and understand solutions to all of problems you've seen above and more!

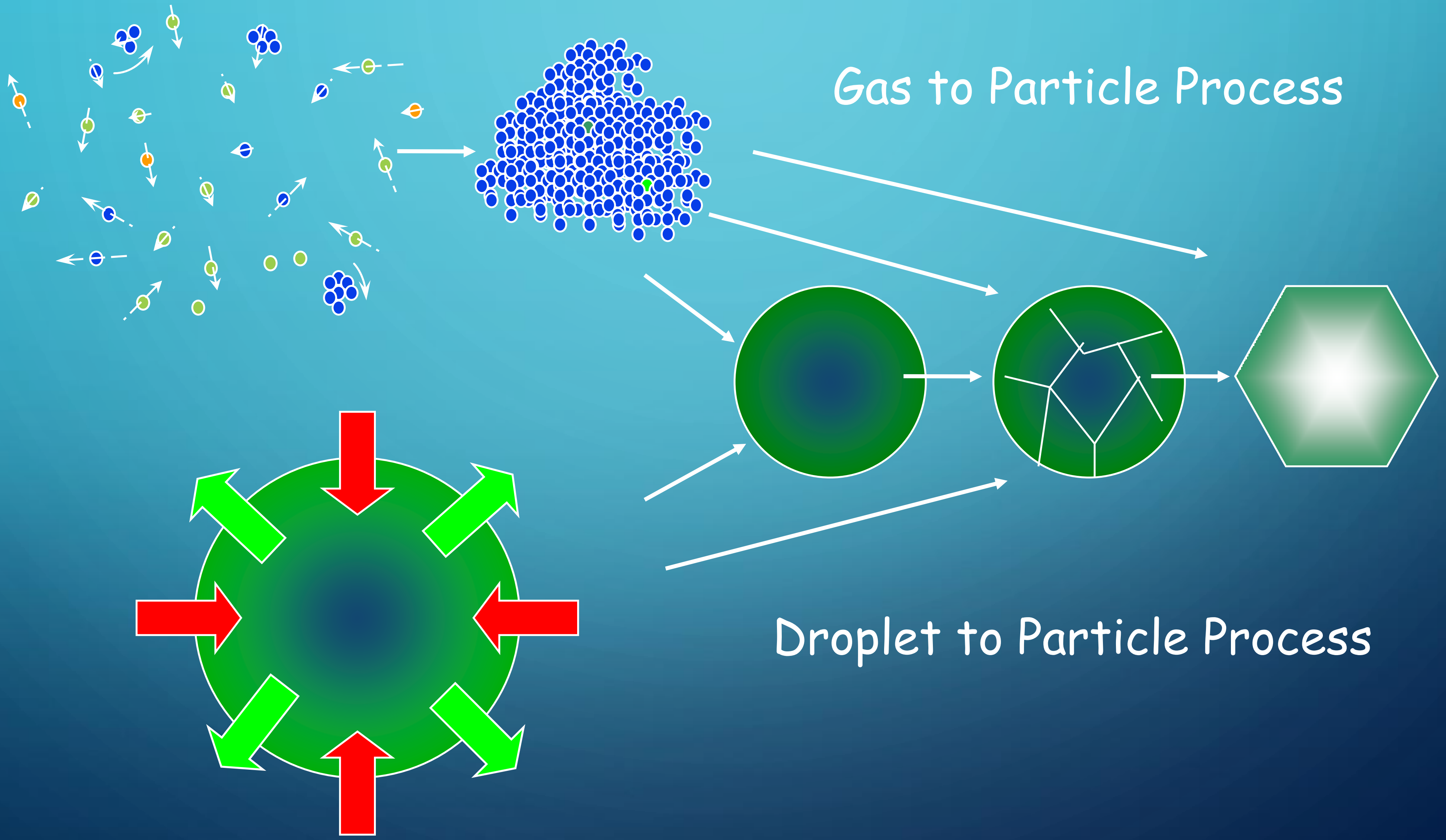
"TBD" TOKEN SOLVES ALL THESE PROBLEMS!

- Here's some of the problems super computers face right now:
  - 1. Slow: Jobs take days to run.
  - 2. Jobs fail often: After you've waited days for the job to complete, you find out you didn't ask the question of the computer properly.
  - 3. Inaccurate software: They're not using the best software for the job. Too many shortcuts are taken, making estimates for things like boundary density, viscosity, etc.
  - 4. Monopoly control of the ecosystem. 1 company has 90% market share, and barely updates it's product for the last 15 years. The faster you want your simulation to run, the more they charge you.

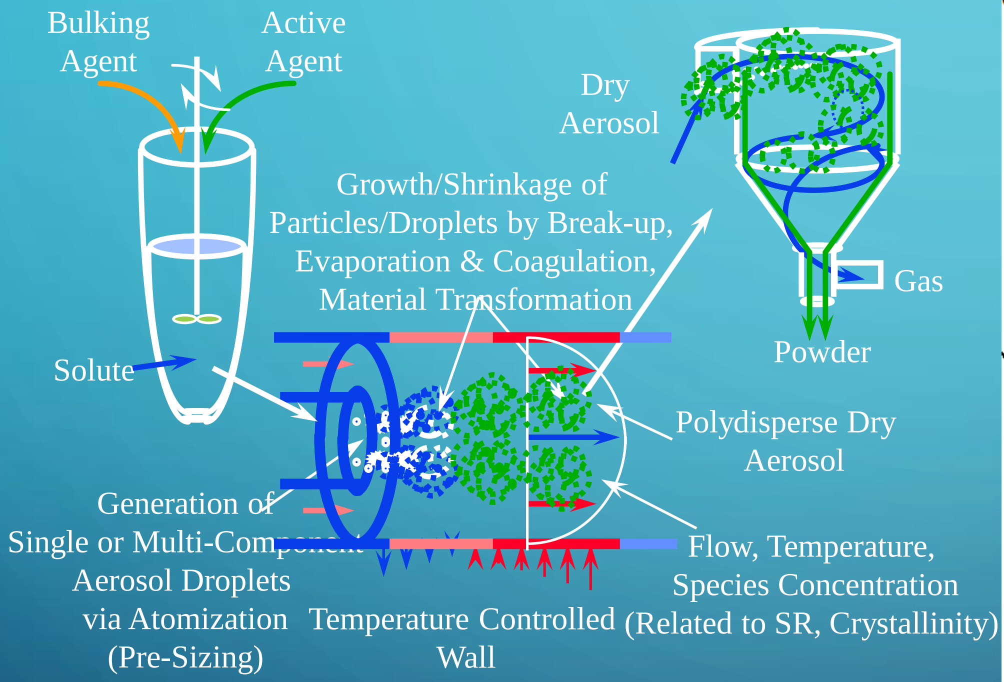
EXAMPLE PROCESSES IN MULTI-PHASE FLOWS

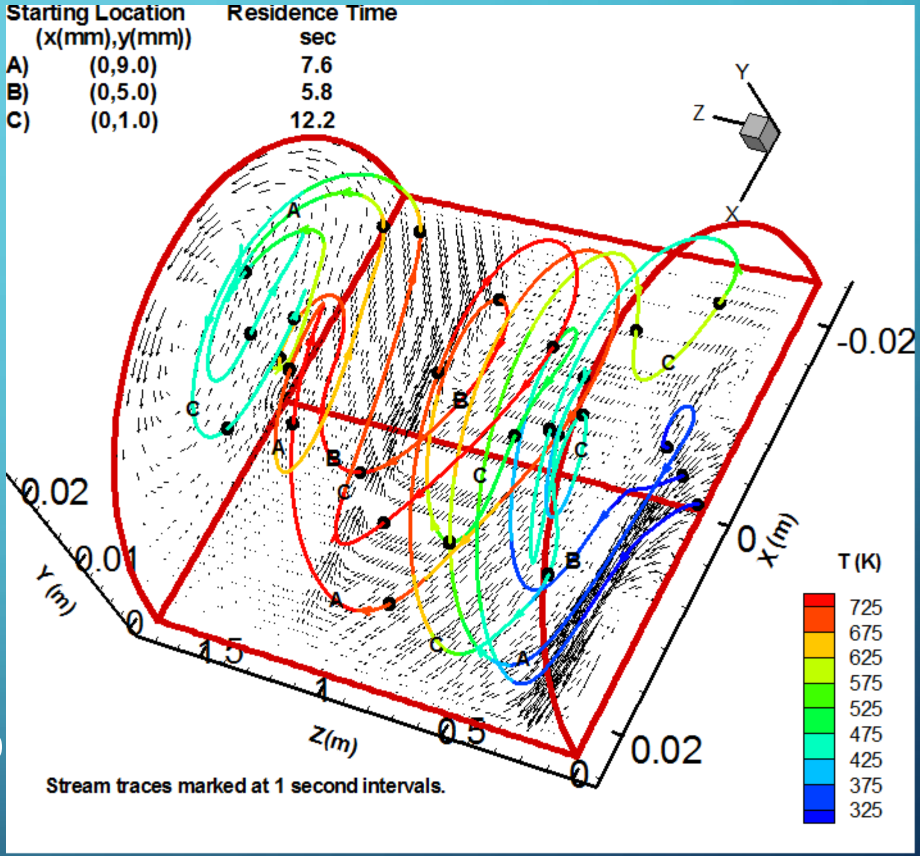
- Particle/Droplet Transport
  - Minimizing surface deposition and losses
    - Gas turbine degradation
    - Ventilation and filter design
  - Maximizing / controlling surface deposition and yeild
    - Administration of pulmonary medicines
    - Application of coatings and films in optical fiber mfg.
- Particle/Droplet Dynamics (Formation and Evolution)
  - Pollution prediction and control
    - Combustion optimization and particle formation in exhausts
  - Particle manufacturing
    - Generation of Powders, Sprays, Nanophase Materials by gas-to-particle and droplet-to-particle processes (see next slide)

EXAMPLE: PROCESS DESIGN ON THE PARTICLE SCALE



EXAMPLE: PROCESS DESIGN ON THE REACTOR SCALE





Calculation of Buoyant Flow in a Microparticle Reactor

COMPARISON OF THE "TBD" TOKEN MODEL TO AVAILABLE COMPETITORS

KEY ELEMENTS OF "TBD" TOKEN MODEL

- Basic Fluid Flow (1-D, 2-D, 3-D, Viscous, Compressible)
  - Internal \ External (e.g. pipes, ducts and rooms \ airplanes, cars)
  - Incompressible \ Compressible \ Transonic \ Supersonic \ Hypersonic (Mach 0–5)
  - Laminar \ Turbulent (e.g. small to large volumes)
  - Strong Coupling to Aerosol Dynamics & Chemistry (e.g. multi-physics)
- Multi-Phase Aerosol Behavior (1-D, 2-D, 3-D, Polydisperse)
  - Aerosol Transport
  - Aerosol Dynamics
- Chemically Reaction (1-D, 2-D, 3-D, Multi Species)
  - Multi Species Transport (Laminar \ Turbulent)
  - Strong Coupling to Aerosol Dynamics & Chemistry
  - Fluid phase and Surface Reactions

EXAMPLES OF COMPETITIVE TECHNOLOGY: AVAILABLE MULTI-PHASE MODELS IN ANSYS*

- Discrete Phase Model (DPM)
- Mixture Model
- Volume of Fluid Model (VOF)
- Eulerian Multiphase Flow Model
- Fine Particle Model (3rd Party Add-On)

*market leading CFD provider holding 90% of market

AVAILABLE MULTIPHASE MODELS IN ANSYS
DISCRETE PHASE MODEL (1/1)

- Trajectories of Particles/Droplets/Bubbles are computed in a Lagrangian or moving reference frame
    - Particles can exchange heat, mass and momentum with the continuous gas phase.
    - Particle-Particle Interaction is neglected
    - Turbulent Dispersion can be modelled with a Stochastic Tracking or a "Particle Cloud" Model
- Volume Loading: Volume Fraction < 12%
- Particulate Loading: Low to Moderate
- Application Examples
    - Cyclones, Spray Dryers, Particle Separation and Classification, Liquid Fuel and Coal Combustion

AVAILABLE MULTIPHASE MODELS IN ANSYS MIXTURE MODEL (1/2)

- Model N-Phase Flows
  - Solve Mixture Momentum equations (for mass-averaged mixture velocity)
  - Inter-phase exchange terms depend on relative (slip) velocities
  - Turbulence and Energy Equations are solved for the Mixture
  - Only one of the phase may be defined as compressible
- Solves the transport equation of volume fraction for each secondary phase

AVAILABLE MULTIPHASE MODELS IN ANSYS MIXTURE MODEL (2/2)

- Flow Regime: Bubbly flow, droplet flow, slurry flow
- Volume Loading: Dilute to moderate
- Particle Loading: Low to moderate
- Turbulence: Weak coupling between phases
- Stokes Number: Stokes Number << 1
- Applications:
  - Hydrocyclones, bubble column reactors, solid suspensions, gas sparging

AVAILABLE MULTIPHASE MODELS IN ANSYS VOLUME OF FLUID (1/2)

- Model to track the position of the interface between two or more immiscible fluids.
- A single momentum equation is solved and the resulting velocity is shared by all phases
- Surface tension and wall adhesion effects can be taken into account.
- Solves transport equation for volume fraction of each secondary phase
- Recommended that simulation be performed in unsteady mode.

AVAILABLE MULTIPHASE MODELS IN ANSYS VOLUME OF FLUID (2/2)

- Flow Regime: Slug flow, stratified/free surface flow
- Volume Loading: Dilute to dense
- Particle Loading: Low to high
- Turbulence: Weak to moderate coupling between phases
- Stokes Number: All ranges of Stokes number
- Applications:
  - Large slug flows, filling, off-shore oil tank sloshing, boiling, coating.

AVAILABLE MULTIPHASE MODELS IN ANSYS EULERIAN MULTIPHASE MODEL (1/2)

- Solves continuity, momentum and energy equations for each phase.
    - Volume fractions characterize equation set for each phase
        - Several models available to define inter-phase exchange coefficients.
        - Strong coupling makes this model more difficult to use than Mixture Model.
    - Euler Granular Option: each granular phase is treated as a distinct interpenetrating granular 'fluid'.
    - Heat Transfer between n-phases: Ranz-Marshall (Euler/Euler), Gunn (Euler/granular) and user-defined models

AVAILABLE MULTIPHASE MODELS IN ANSYS EULERIAN MULTIPHASE MODEL (2/2)

- Applicability
  - Flow Regime: Bubbly flow, droplet flow, slurry flow, fluidized beds, particle-laden flows
  - Volume Loading: Dilute to dense
  - Particulate Loading: Low to high
  - Turbulence Weak to strong coupling between phases.
  - Stokes Number: All ranges of Stokes number
- Application Examples
  - High Particle loading flows, slurry flows, sedimentation, hydro-transport, fluidized beds, risers, packed bed reactors

THIRD PARTY ADD-ON
FINE PARTICLE MODEL (FPM) OF CHIMERA TECHNOLOGIES

- Based on a multi-modal lognormal moment model similar to that of "TBD" token but less general.
- Available as a user defined function (UDF) in Fluent
- Applicability
  - Flow Regime: Fine particle aerosol flow
  - Volume Loading: Dilute
  - Particulate Loading: Low
  - Turbulence No coupling between phases.
  - Stokes Number: Zero Stokes number limit
- Application Examples
  - Fine particle deposition, nanomaterials processing, atmospheric dispersion

PROVEN "TBD" TOKEN APPLICATIONS

- Prediction/Minimazation of Atmospheric Deposition
- Prediction/Minimazation of Heat Exchanger Fouling
- Aerosol Control in Nuclear Reactors
- Design of Particle Characterization Equipment
- Design of Dry Particle Inhalers
- Design of Nebulizer Pulmonary Drug Delivery Systems
- Design of Photocatalytic and Optical Particle Synthesis Processes
- Design of High Surface Area Metal Catalyst Particle Synthesis Processes Design of Nanostructured Doped Silica Particles for Fiber Optic Preform Manufacture.
- Design of Gas Phase Catalyst Synthesis Processes
- Design of Carbon Nanotubes and Nano Onions Synthesis Processes
- Design of Nanostructured Inhalable Drug and Drug Carrier Particle Synthesis Processes
- Design of Nano-drug Particle Synthesis Processes
- Design of Nano-particle Deposition Process
- Etc.

OVERVIEW OF SUB-MODEL VALIDATION CASES

Calculated System	Validation Source (E=Experimental, T=Theoretical, M=Model)
Particle coagulation in uniform flow.	Lee & Chen ,1984 (T,M), Pratsinis, 1988 (E, T), Lee et al,1984 (T), Freidlander, 1977 (T)
Laminar 2-D channel flow	Schlicting, 1975 (T)
Laminar 3-D flow in a 90 degree bend	Hille et al.,1985 (E, M)
Laminar and Turbulent flow over 2-D and 3-D backsteps	Srinivasan and Rubin, 2002 (E, M)
Steady and unsteady supersonic flow in a VDC engine inlet	Saunders and Keith, 1991(E, M)
Depositional efficiency due to diffusion in channel flow	Hinds, 1982 (E,T)
Deposition due to diffusion & thermophoresis in channel flow	Chang et al., 1990 (E, T)
Heat transfer and buoyancy in a furnace reactor	Brown, 1997 (M)
Particle deposition in a cooled turbine cascade	Brown et .al., 1996 (M, T)
Condensation shock formation in wet steam nozzle	Moore et al., 1973 (E, T, M)
Argon particle nucleation in a converging nozzle	Wu & Biswas, 1996 (T, M)
Copper nanoparticle formation in a laminar flow reactor	Nasibulin et al, 2001 (E)
Methane/air combustion in 1-D flow	Kee et al., 1985 (M)
Hydrogen/air combustion kinetics in a supersonic flow	Hagenmaier, 1997 (E, M)
CsOH aerosol dynamics & transport in a laminar flow reactor	Pyykönen et al., 2002 (M)
Photocatalytic reduction of organics on a reacting surface	Yamashita et al., 1997 (E)
Unsteady turbulent flow in a dry particle inhaler	Brown et al, 2003 (E)
Thermal decomposition of $Cu(acac)_2$ in a laminar flow reactor	Nasibulin et al, 2001 (E)
Sulfuric acid aerosol formation in a HSCT nozzle and plume	Miake-Lye et al., 1993 (E, T), Appleman, 1953 (E, T, M)

COMPARISON OF THE ”TBD” TOKEN METHOD TO COMPETITORS

EFFICIENT CFD FOR SINGLE PHASE FLOWS:
THE BULK FLOW SOLVER

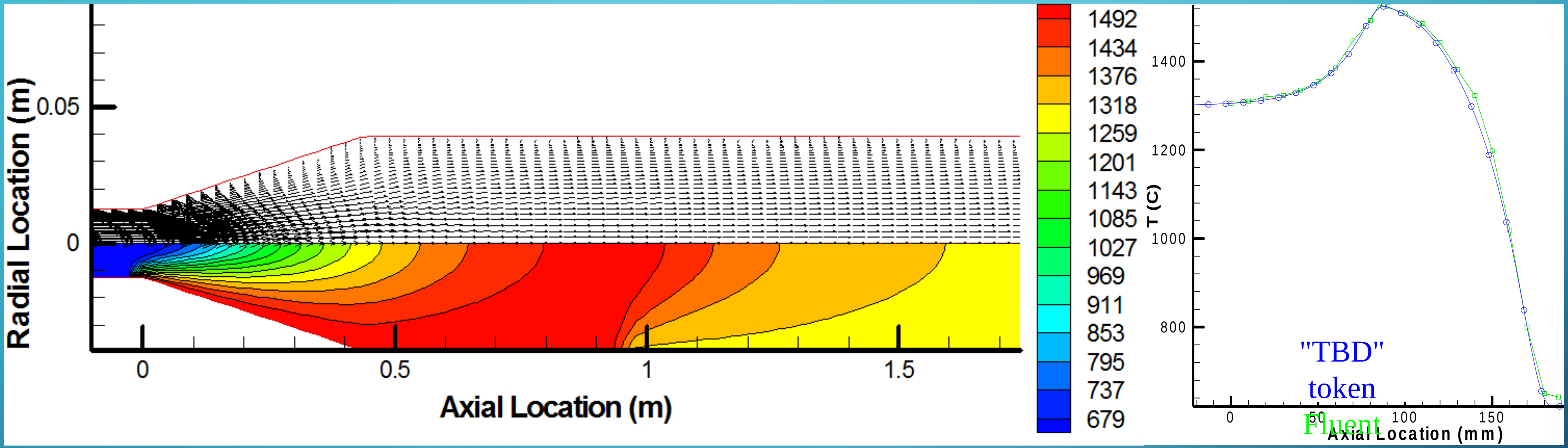
"TYPICAL" CFD SOLVER (AS IN ANSYS)

- Time-marching procedures requiring a transient solution to reach Steady State (time step limited by strict CFL conditions)
- Boundary conditions are approximate
- Fully explicit or only point or line implicit
- Based on SIMPLE, SIMPLEC or other 40 year old Pressure Relaxation Techniques
- Accelerated and Stabilized by
  - Multi-Grid
  - Matrix Preconditioners
  - Upwinding and Complex Roe / Van Leer Flux-Splitting (physically incorrect)
  - Significant Artificial Damping (physically incorrect)
- Add-ons are numerically only loosely numerically coupled
- Result: It takes a long time to converge to an inaccurate solution

THE "TBD" TOKEN CFD SOLVER

- Based on the Reduced Navier-Stokes (RNS) plane implicit spatial marching technique
- Boundary conditions are physically correct
- Requires no time-accurate transient solution to reach the steady state (no "CFL" time step condition)
- Requires no artificial viscosity
- Separate pressure and convective flux splitting
- Heat transfer, species-chemical reactions and particle phase transport and dynamics are fully integrated into the solution algorithm
- Efficient, stable and accurate
- Result: It takes a short time to converge to an accurate solution

COMPARISON OF FLUENT/ANSYS AND "TBD" TOKEN
FOR FLOW WITH HEAT ADDITION (CONVERGENCE AND ACCURACY)



Code	Time	Required Grid	Error	Iterations
SW	~ 3.1 mins	85 x 31	1e-8	92
ANSYS	~ 28 mins	150 x 50	1e-6	22188

FLOW MODEL: FULL NAVIER-STOKES (FNS)

$$diag\left(1,1,1,1,\frac{1}{\rho_f}\right)\frac{\partial}{\partial t}\left[\sqrt{g}\begin{pmatrix}\rho \\ \rho u_f \\ \rho v_f \\ \rho w_f \\ H_t-(\gamma-1)M^2P\end{pmatrix}\right]+\frac{\partial}{\partial \xi}\left[\sqrt{g}\begin{pmatrix}\rho U_f \\ \rho U_f u_f+\xi_x P-\tau_x{}^{\xi} \\ \rho U_f v_f+\xi_y P-\tau_y{}^{\xi} \\ \rho U_f w_f+\xi_z P-\tau_z{}^{\xi} \\ U_f H_t-\Phi_\xi+q_\xi\end{pmatrix}\right]$$

$$+\frac{\partial}{\partial \eta}\left[\sqrt{g}\begin{pmatrix}\rho V_f \\ \rho V_f u_f+\eta_x P-\tau_x{}^{\eta} \\ \rho V_f v_f+\eta_y P-\tau_y{}^{\eta} \\ \rho V_f w_f+\eta_z P-\tau_z{}^{\eta} \\ V_f H_t-\Phi_\eta+q_\eta\end{pmatrix}\right]+\frac{\partial}{\partial \zeta}\left[\sqrt{g}\begin{pmatrix}\rho W_f \\ \rho W_f u_f+\zeta_x P-\tau_x{}^{\zeta} \\ \rho W_f v_f+\zeta_y P-\tau_y{}^{\zeta} \\ \rho W_f w_f+\zeta_z P-\tau_z{}^{\zeta} \\ W_f H_t-\Phi_\zeta+q_\zeta\end{pmatrix}\right]=\begin{bmatrix}\Delta m \\ \rho g_\xi \\ \rho g_\eta \\ \rho g_\zeta \\ \Delta H_t\end{bmatrix}$$

REDUCING THE PROBLEM TO ALGEBRA

- Ax = b --------> x = A^{-1}b

75x75x75 grid (421,875 points), 6 variables

2,531,250 unknowns, $6.4\text{x}10^{12}$ elements of A!

$$\underbrace{\begin{bmatrix} 5.4 & 1.2 & 0.0 & 6.3 & 0.0 & 0 & 0 & \ldots \\ 8.8 & 3.9 & 5.4 & 9.3 & 0.0 & 0 & 0 & \ldots \\ 0.0 & 2.5 & 1.4 & 6.7 & 8.7 & 0 & 0 & \ldots \\ \ldots. & \ldots. & \ldots. & \ldots. & \ldots & \ldots & \ldots & \ldots \end{bmatrix}}_{\text{Coefficient Matrix}} \begin{bmatrix} x_1 \\ x_2 \\ \ldots \\ \ldots \end{bmatrix} = \begin{bmatrix} 9 \\ -3 \\ \ldots \\ \ldots \end{bmatrix}$$

Unknowns RHS

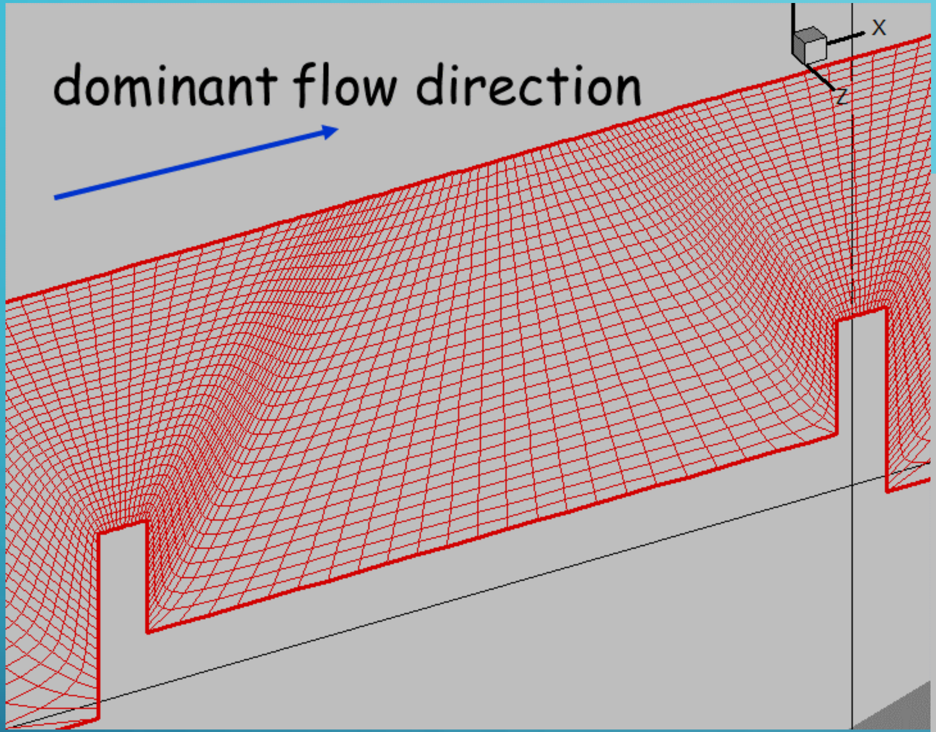
HOW TO GET A^{-1}

- Direct Methods (Implicit)
  - Cramer's Rule: $(N+1)!$ Operations
  - Gausian Elimination: N^3 Operations
  - Singular Value Decomp. N^2 Operations
  - Thomas Algorithm: $3N$ Operations
  - Sparse Martix Methods: $5N$ Operations
- Iterative Methods (Explicit)

LIMITATIONS FOR CFD ALGORITHMS

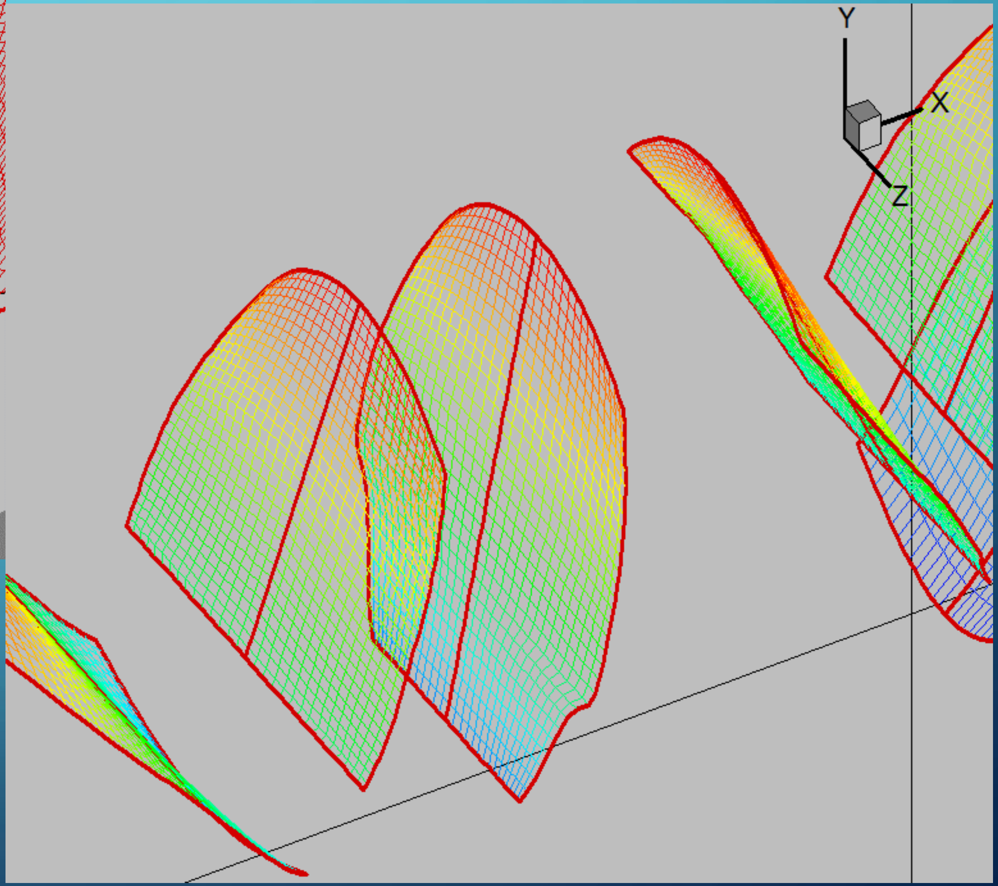
- It is impossible to get a solution to a nonlinear PDE in one iteration
- For a system of fluids PDEs, it is impossible to solve a whole 3D domain at once except for very small cases (approximately 15x15x15 on our computers)
- For additional equation sets, problems get worse
- To get solutions to realistic problems have to break the system down
  - Equation sets
  - Multiple domains
  - Explicit schemes that don't require matrix inversions
  - Multi Step schemes
  - Point, line or plane implicit schemes
- In general, the more implicit you are, the more stable your solution method and the fewer steps to converge

HOW ITS DONE IN "TBD" TOKEN: PLANE MARCHING IN 3-D



<- Symmetry Plane

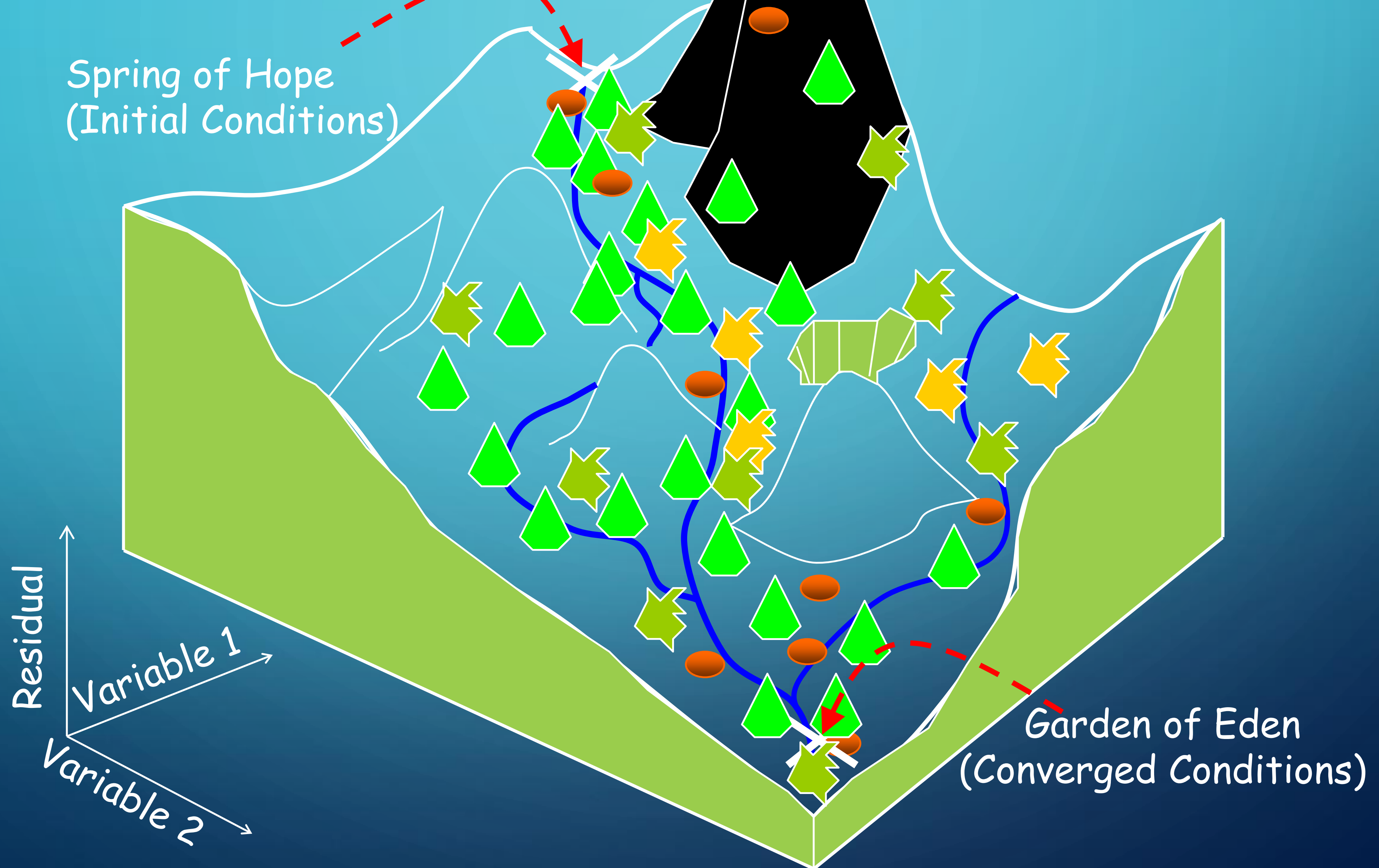
Marching Plane ->



CONVERGENCE ACCELERATING FEATURES

- Reduced Navier-Stokes formulation with Deferred Corrector
    - Simplified Residual Space
- Space Marching with Pressure Flux Splitting
    - Infinite time step (no CFL condition)
    - Single sweep solutions for supersonic flows.
    - Backsweeping for fast pressure relaxation
- Equation Staggering
    - Assures diagonal dominance without preconditioning
    - Allows fewer grid points, small domains and thus reduced computation size
    - No artificial viscosity reduces stencil size and coefficeint matrix density
- Plane Implicit
    - Local solutions are “stable” without underrelaxation
- Solved in Delta Form
    - Multiple back-substitutions of each LU Decomposition ($b=A^{-1}x$)
- Continuity always 100% satisfied
    - No Poisson Solver for Pressure Relaxation

TRAVELING IN RESIDUAL SPACE



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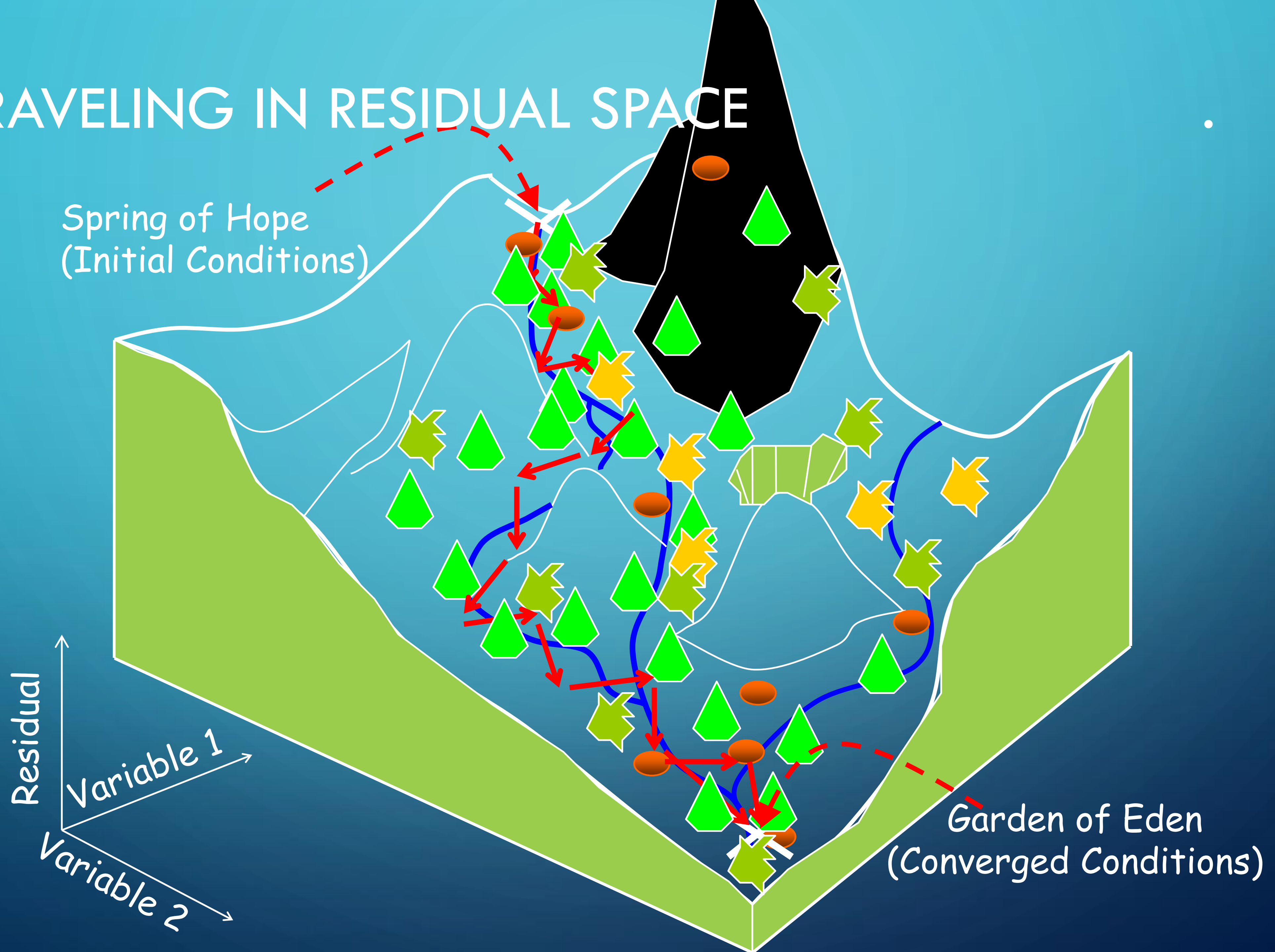

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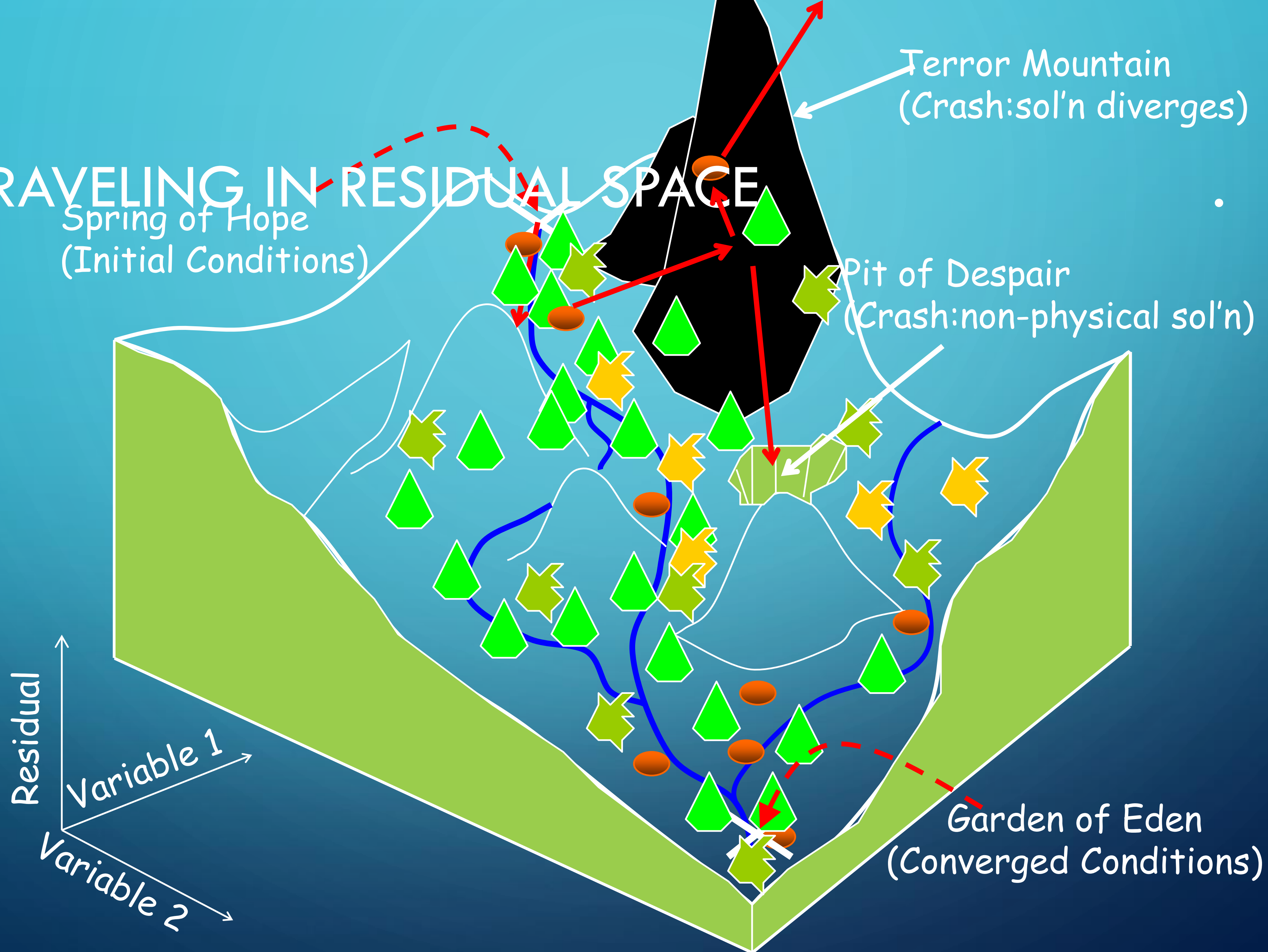

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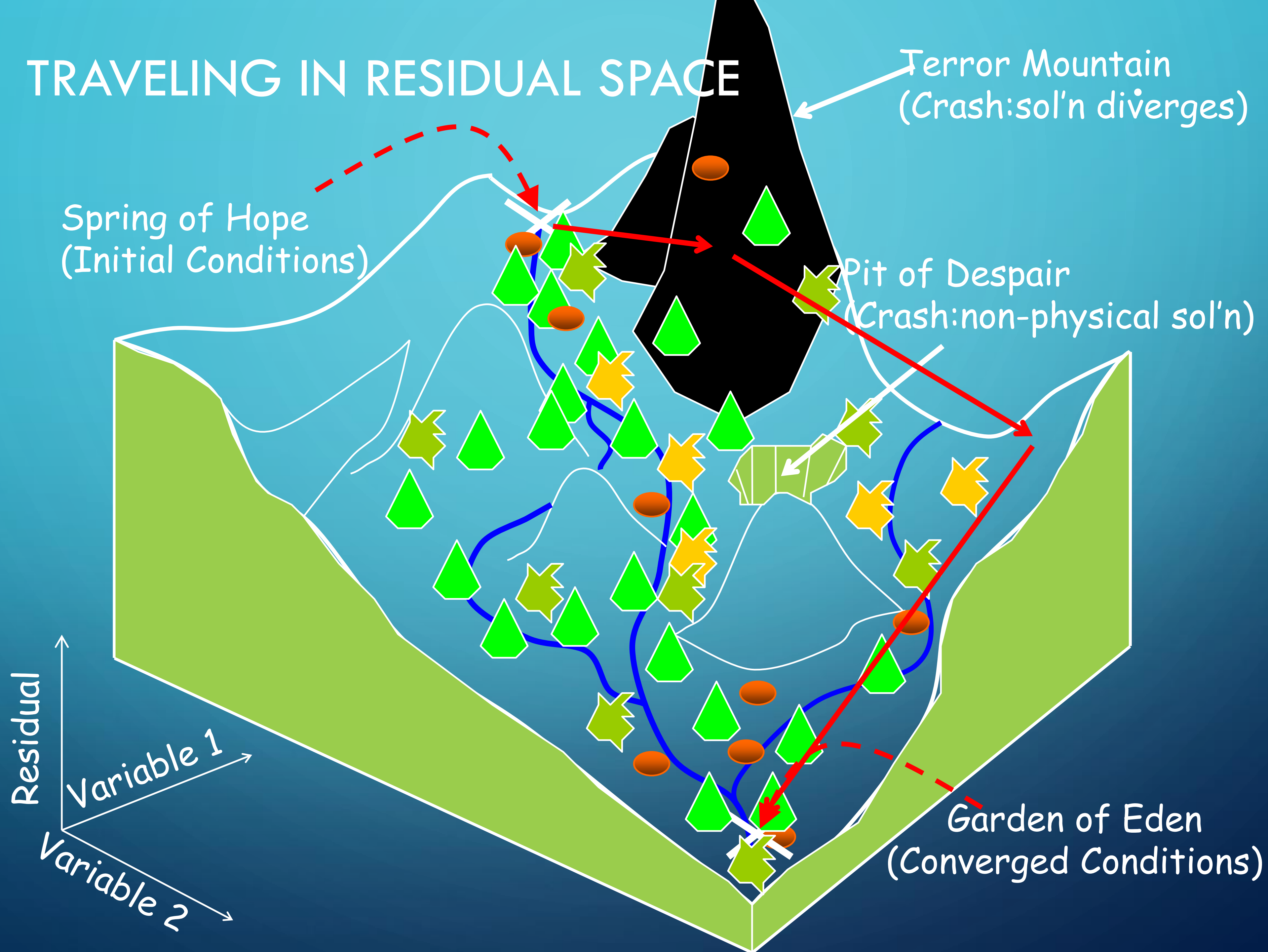
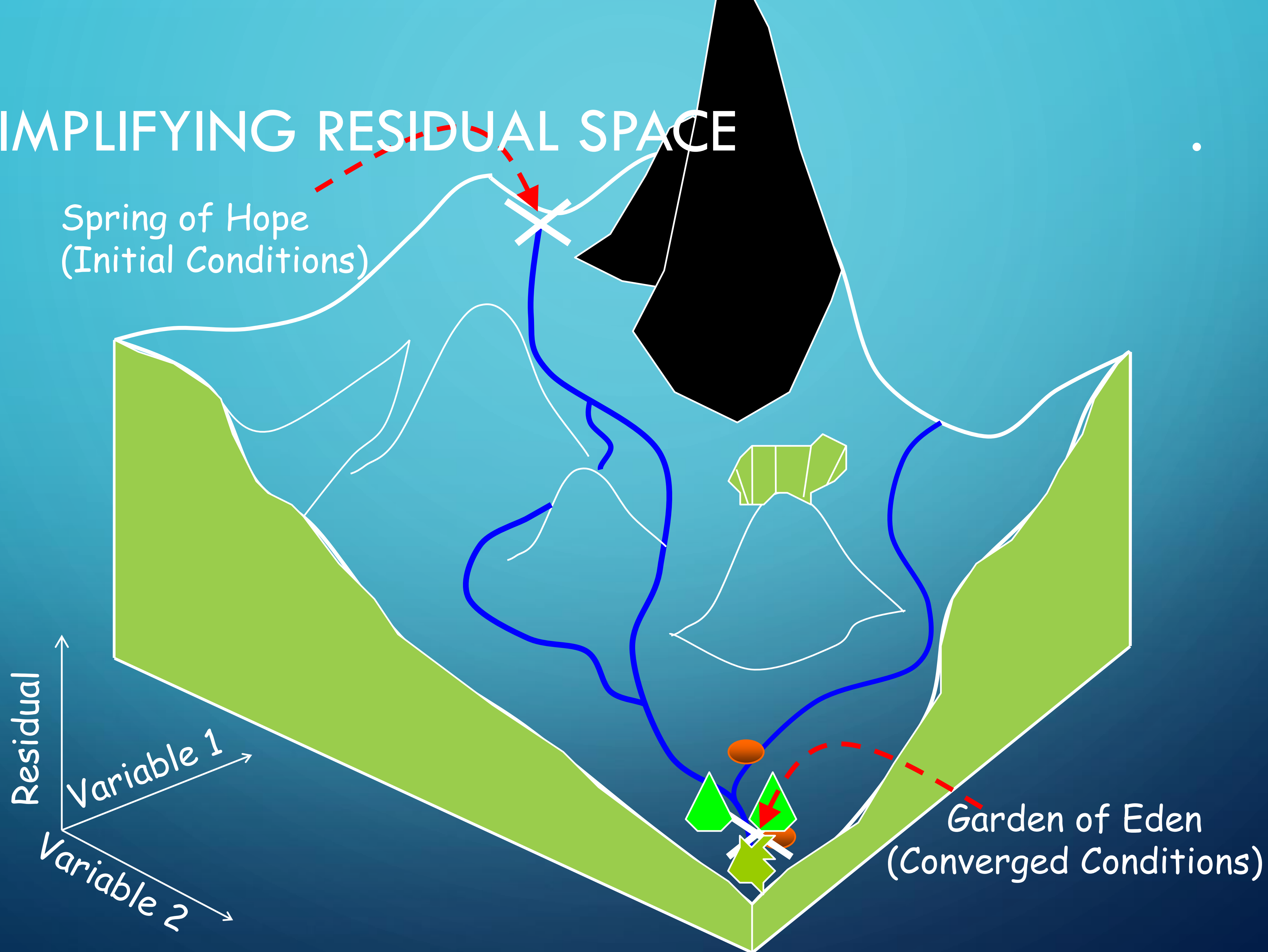
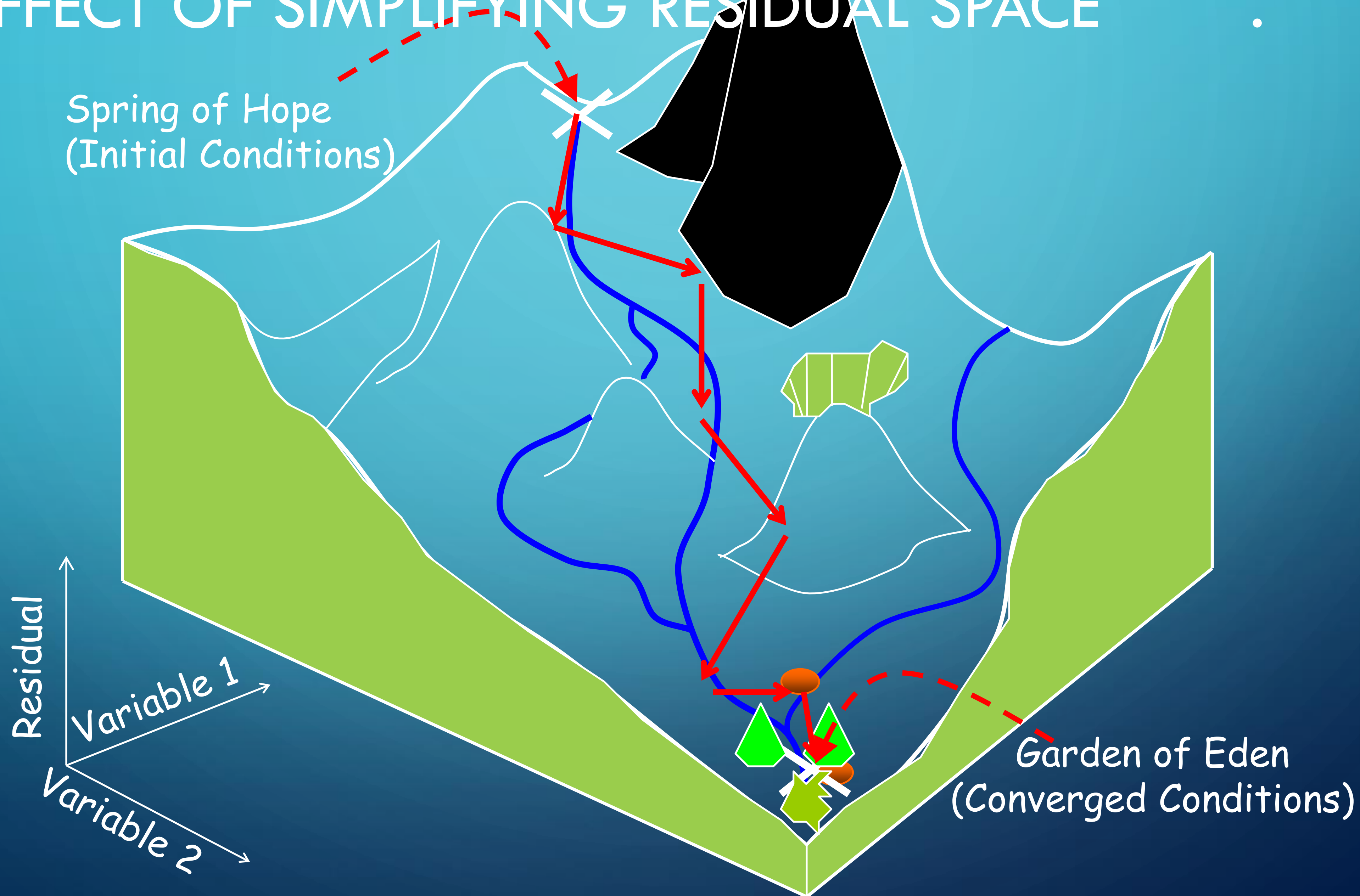


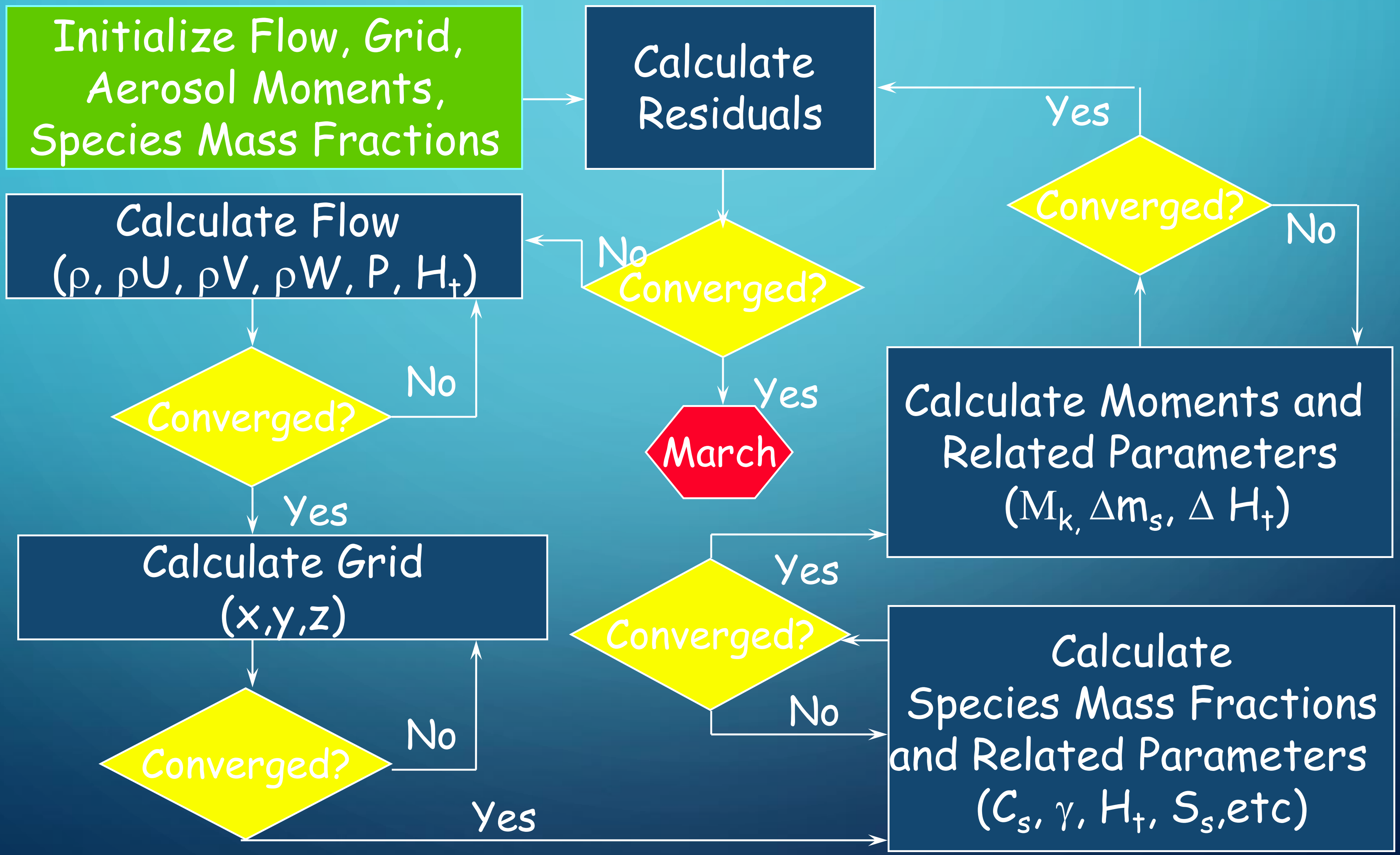
SIMPLIFYING RESIDUAL SPACE



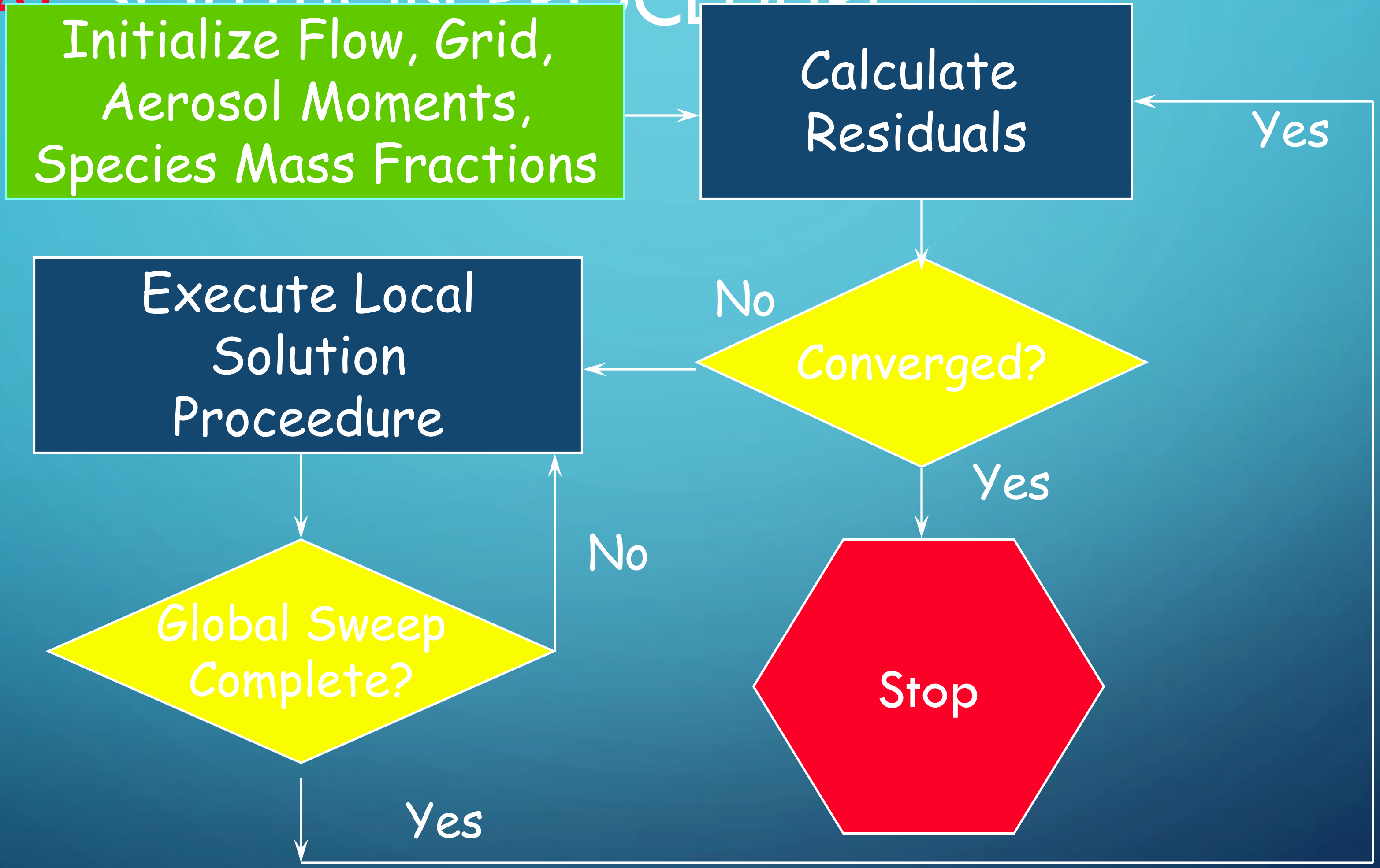
EFFECT OF SIMPLIFYING RESIDUAL SPACE



LOCAL SOLUTION PROCEDURE



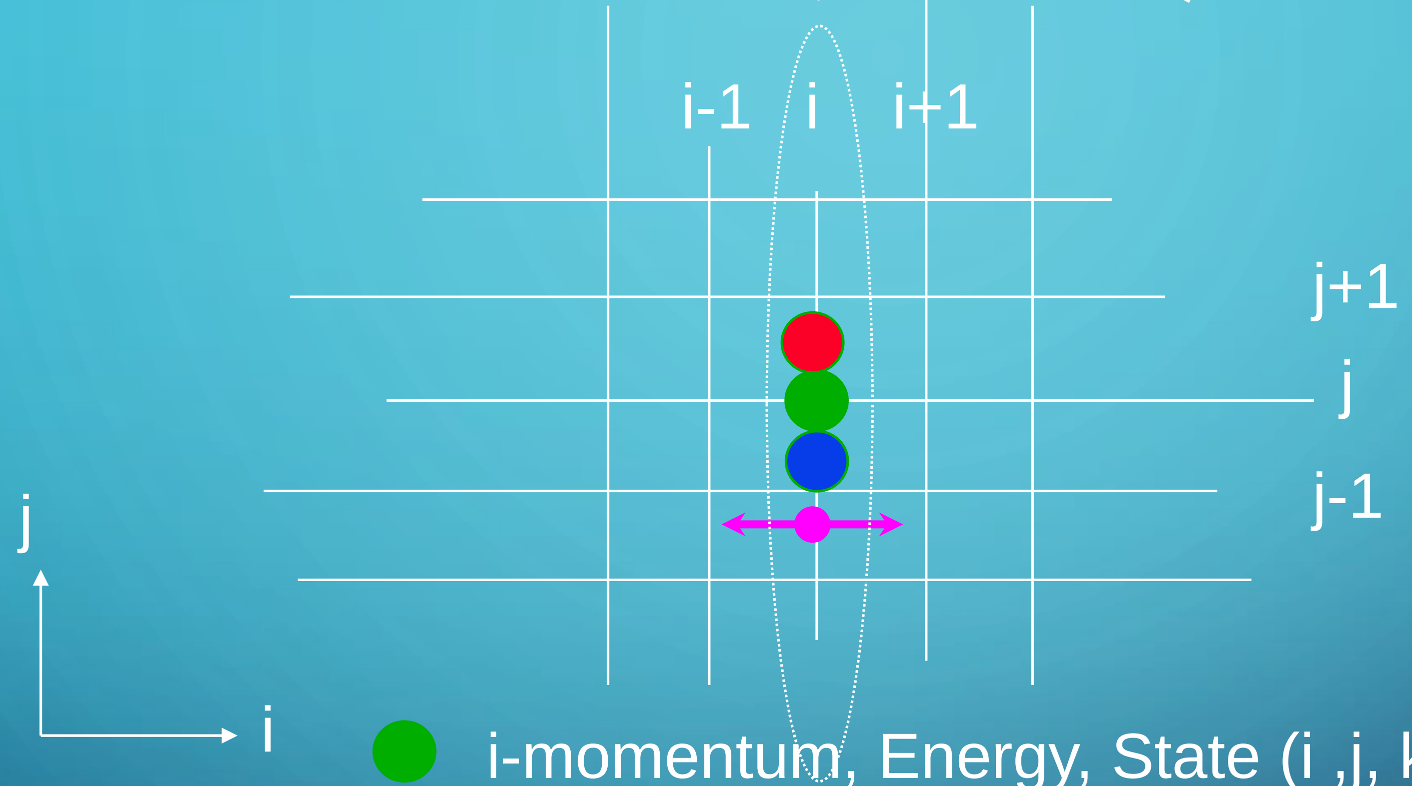
GLOBAL SOLUTION PROCEDURE



ACCURACY ENHANCING FEATURES

- Generalized Curvelinear Coords. & GIE Source Terms
  - Arbitrary Structured Grids w/o orthogonality constraints
  - Greatly reduces grid related metric errors in solution
- Transformed Coordinates for Transformed Velocity
  - Velocities in Conserved Variable Form (ρU), Ht vs. T
- Equation Staggering
  - 2nd order accuracy without oscillations (no odd-even decoupling)
  - Allows physically correct and consistent treatment of BCs
  - Eliminates spurious solutions due to BC influences
- Independent Pressure and Convective Fluxes
  - Preserves mathematical characteristics of governing equations
  - Insures all boundary conditions are physically correct over all Mach numbers
- Consistent Boundary Conditions (P and V)
  - Allows boundaries to be set close to action
- Spacial Marching with Pressure Flux Splitting
  - Continuity always 100% satisfied

"TBD" TOKEN MARCHING TECHNIQUE (MARCHING DIRECTION, I-J PLANE)



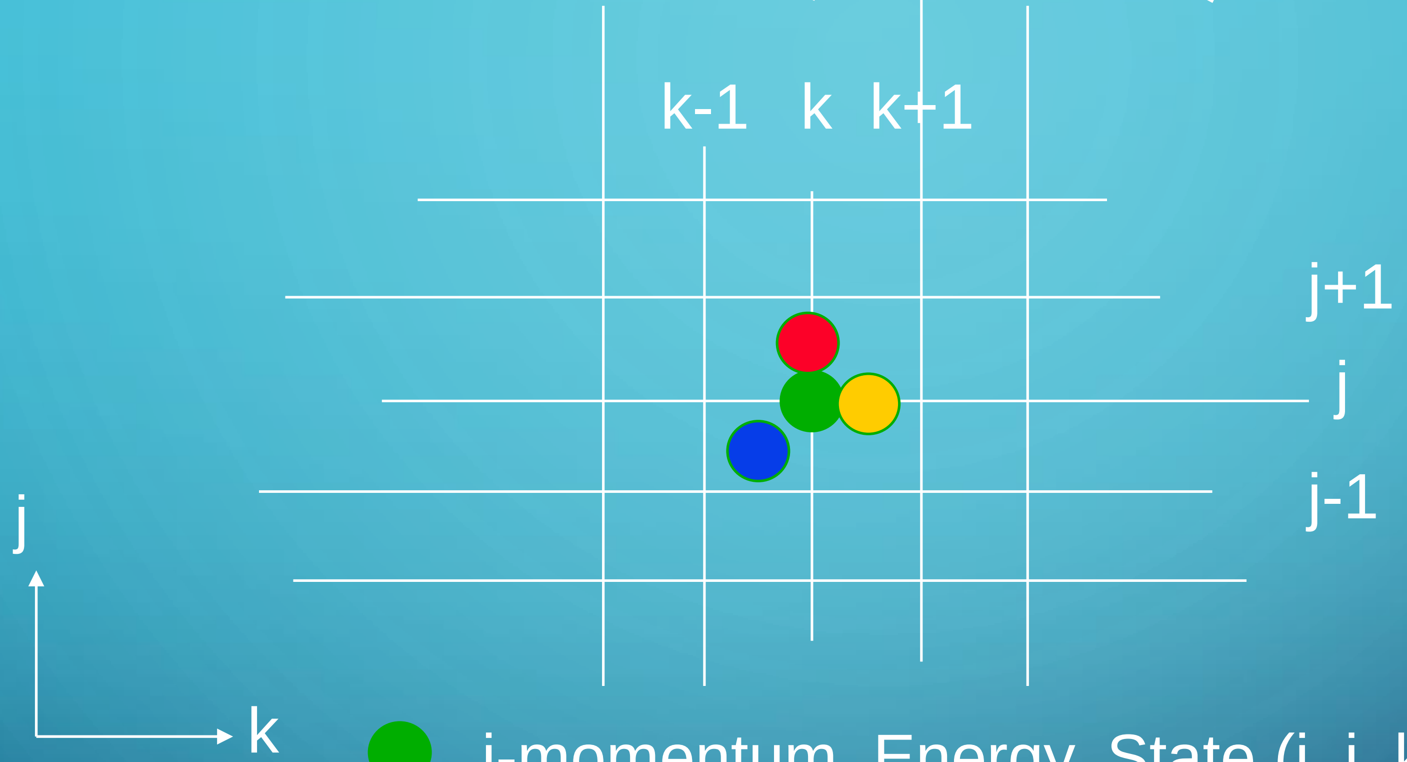
i-momentum, Energy, State (i ,j, k location)

j-momentum (i,j+½,k location)

Continuity (i, j-½, k-½ location)

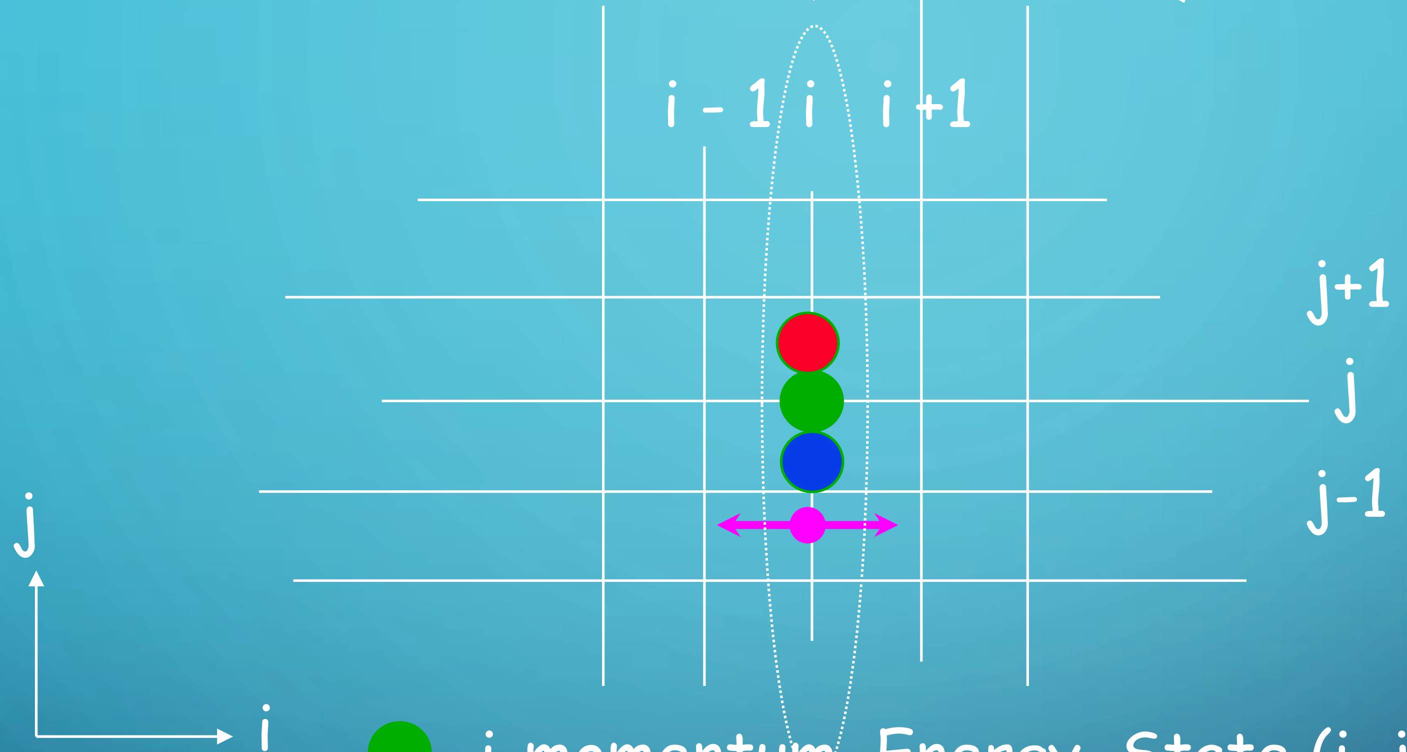
k-momentum not shown (i, j, k+½, location)

"TBD" TOKEN MARCHING TECHNIQUE (MARCHING DIRECTION, J-K PLANE)



- i-momentum, Energy, State (i ,j, k location)
- j-momentum (i,j+½,k location)
- Continuity (i, j-½, k-½ location)
- k-momentum (i, j, k+½, location)

CURRENT MARCHING TECHNIQUE (MARCHING DIRECTION, I-J PLANE)



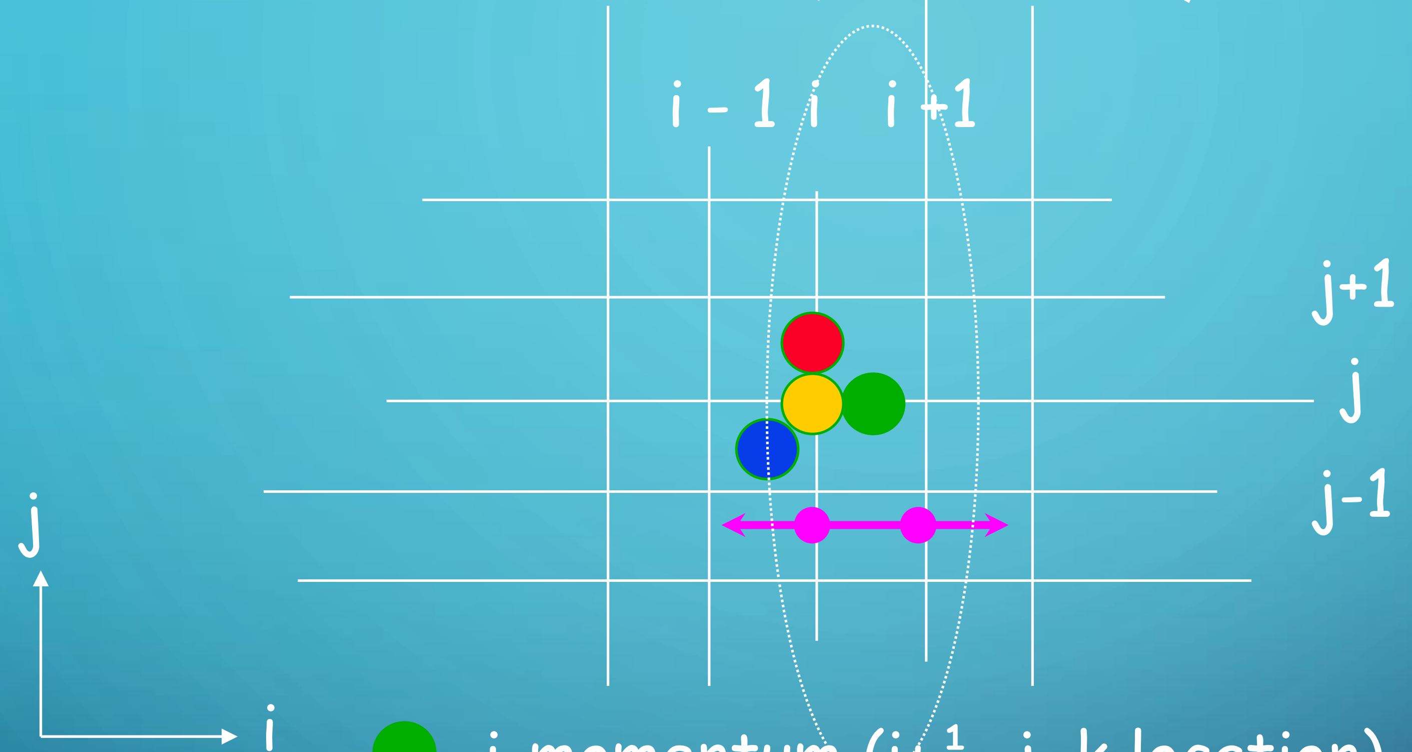
i-momentum, Energy, State (i ,j, k location)

j-momentum (i,j+$\frac{1}{2}$,k location)

Continuity (i, j-$\frac{1}{2}$, k-$\frac{1}{2}$ location)

k-momentum not shown (i, j, k+$\frac{1}{2}$, location)

NEW "VOLUME MARCHING" TECHNIQUE (MARCHING DIRECTION, I-J PLANE)



i-momentum ($i+\frac{1}{2}$, j, k location)

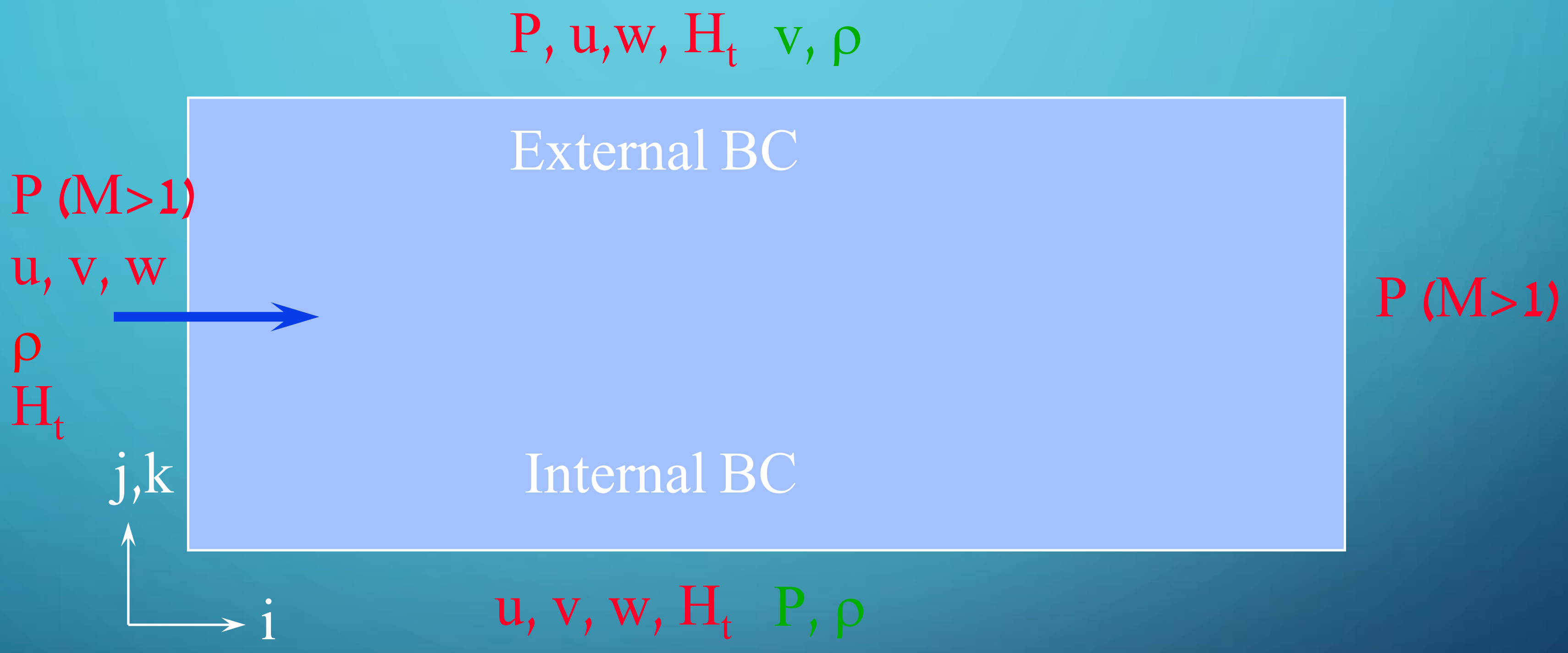
j-momentum (i, $j+\frac{1}{2}$, k location)

Continuity ($i-\frac{1}{2}$,$j-\frac{1}{2}$,$k-\frac{1}{2}$ location)

Energy, State (i, j,k location)

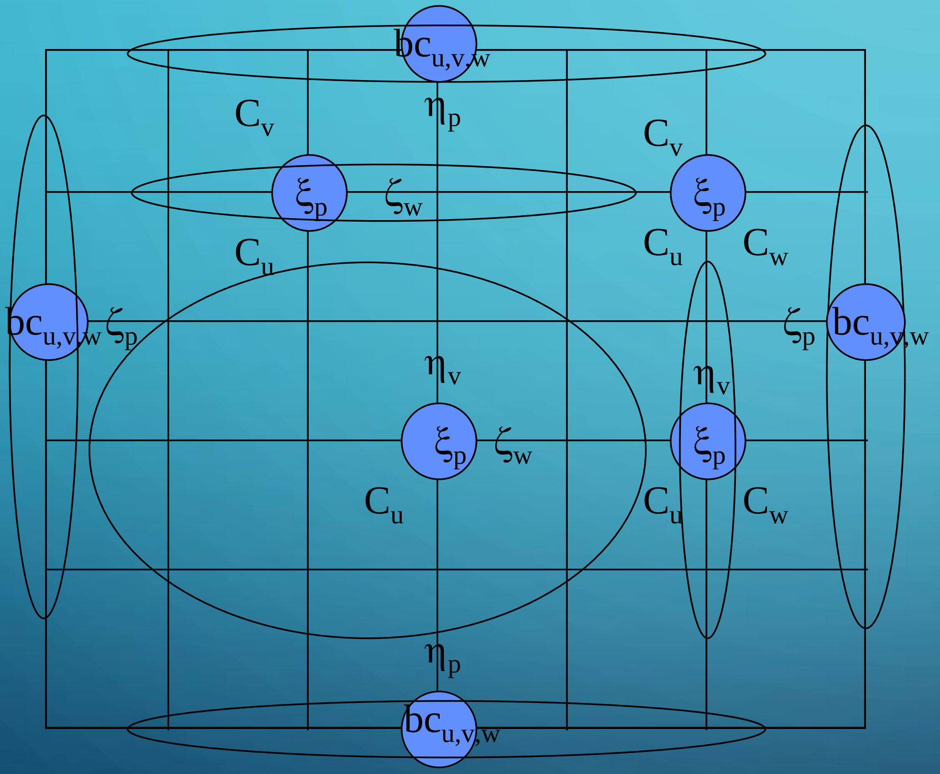
k-momentum not shown (i ,j, $k+\frac{1}{2}$, location)

"TBD" TOKEN BOUNDARY CONDITIONS

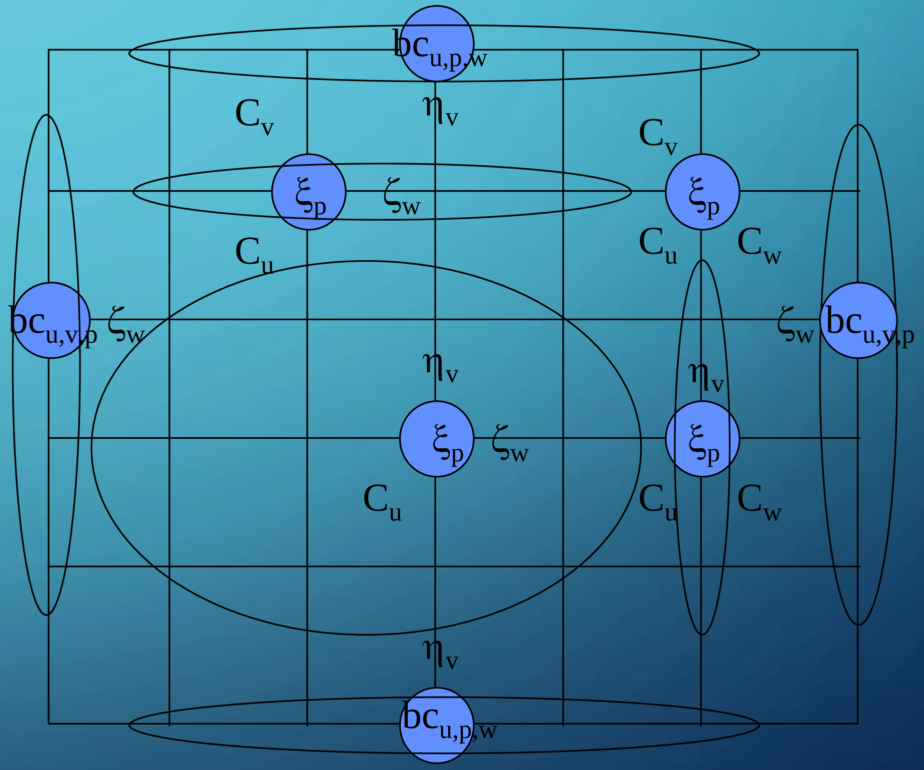


CROSS STREAM BOUNDARY CONDITIONS

Internal Flow



External Flow



WHY DEFER AXIAL DIFFUSIVITY?

- In the Steady-State
  - "TBD" token velocity gradients (t_{xx} t_{xy}) << Normal velocity gradients (t_{yy}, t_{yz})
  - Majority of flow domain is "Inviscid"
    - High shear only occurs locally and perpendicular to the flow direction (e.g very close to walls/jets)
  - Except
    - Re very small (Re<10)
    - Normal Shocks (Momentum & Pressure forces dominate)

$$\tau_{xx} = \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right)$$

PRESSURE FLUX SPLITTING

- Acoustic Flux vs. Convective Flux
  - Convective flux travels in flow direction
  - Acoustic flux travels along characteristics

$$\frac{\partial \mathrm{p}}{\partial \xi} = \omega_{1-1/2}\frac{\left(\mathrm{p}_i - \mathrm{p}_{i-1}\right)}{\left(\xi_i - \xi_{i-1}\right)} + \left(1 - \omega_{1+1/2}\right)\frac{\left(\mathrm{p}_{i+1} - \mathrm{p}_i\right)}{\left(\xi_{i+1} - \xi_i\right)}$$

$$\omega = \min\left(\mathrm{M}_{\xi}{}^{2}, 1\right)$$

“DELTA” FORM

- $Ax = b$ --------> $x = A^{-1}b$
- $A(x-dx) = b - A\,dx$

  or

- $A\,dx = \underline{A(x+dx)-b} = b'$ --------> $dx = A^{-1}b'$

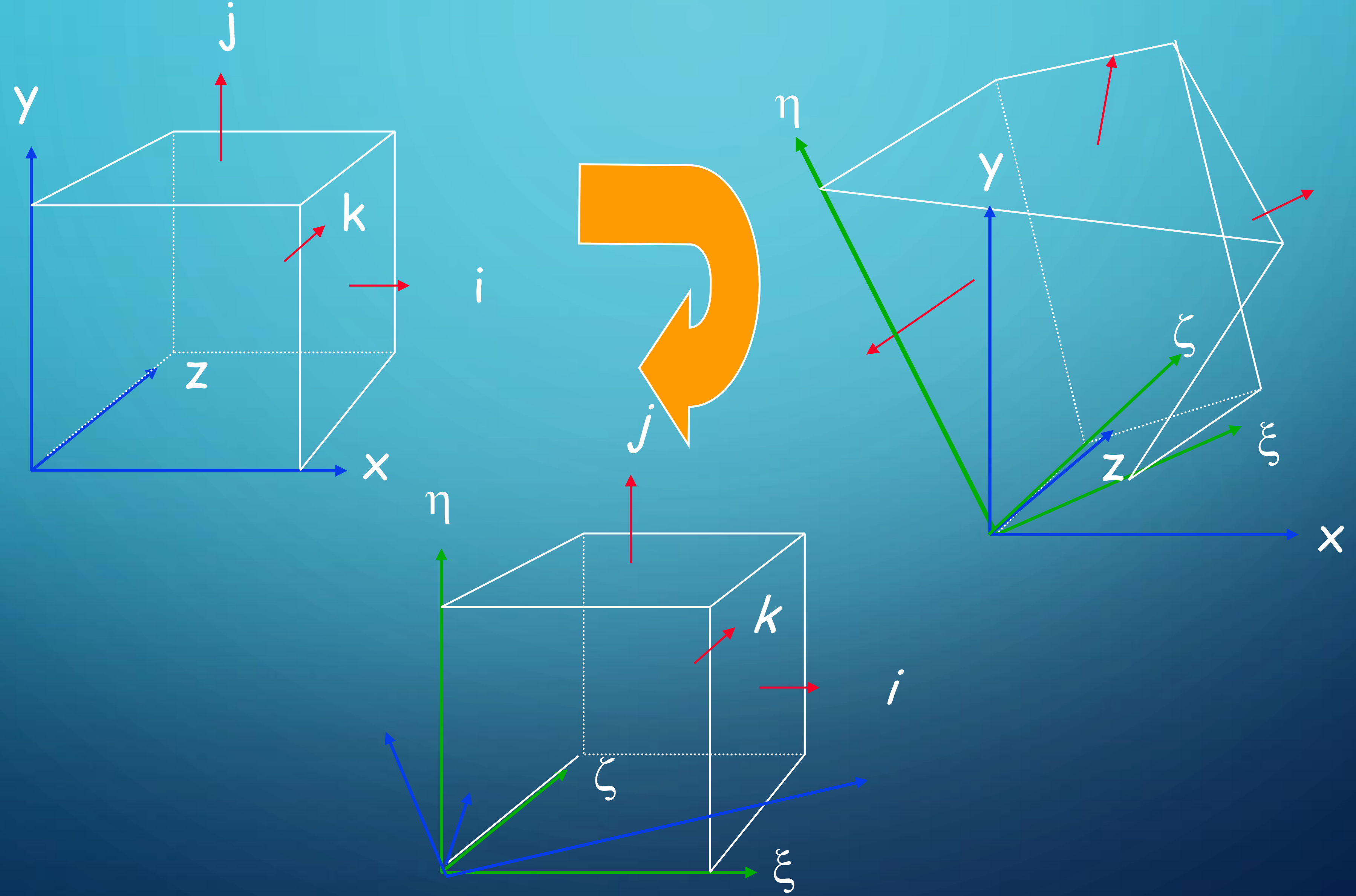
  RHS is now the error (residual)

- As dx -----> 0 (as the solution converges)

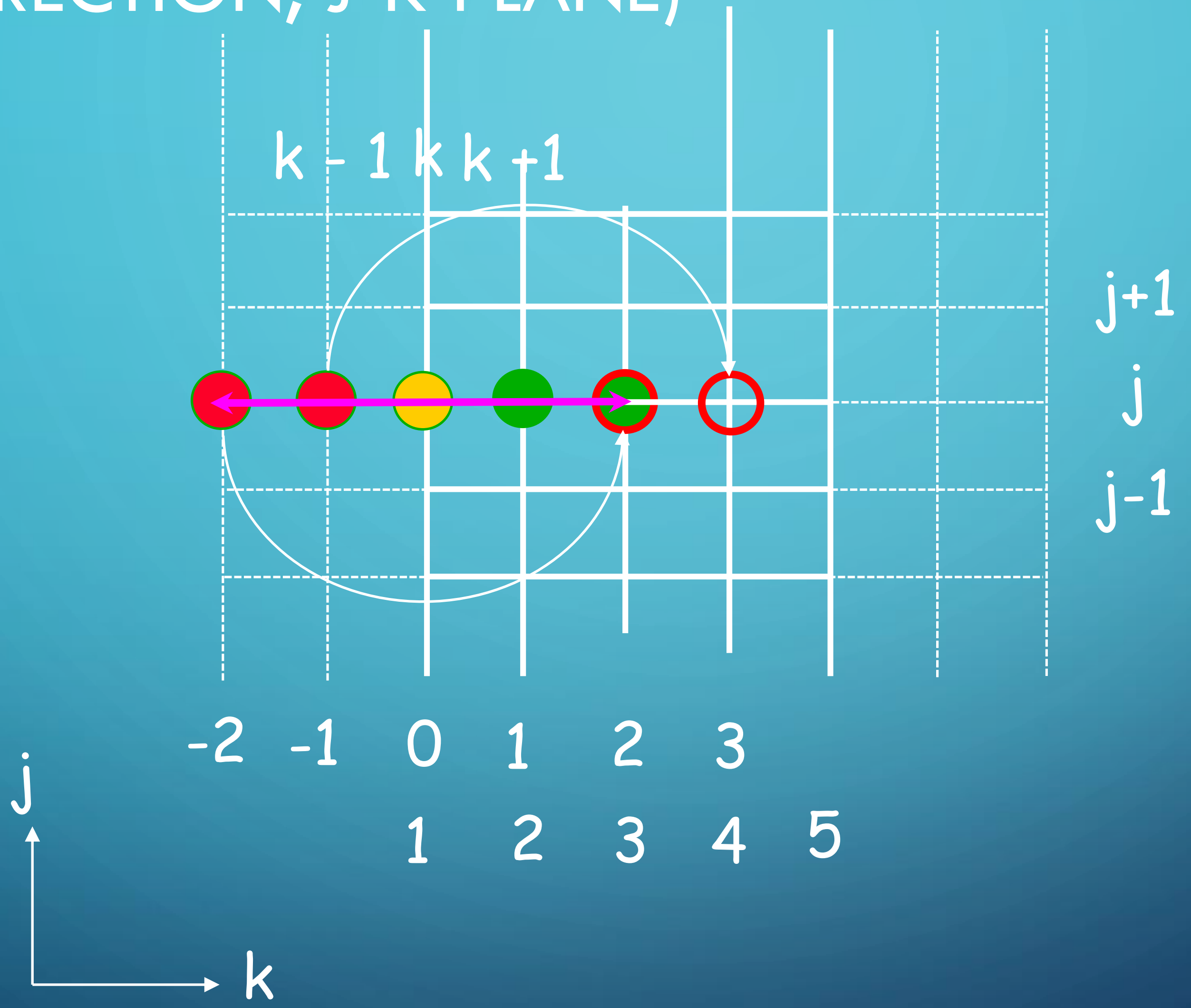
  b' -----> 0

- *A^{-1} does not have to be exact*
- Thus $a^{-1} \approx A^{-1}$ & $dx = a^{-1}\,b'$

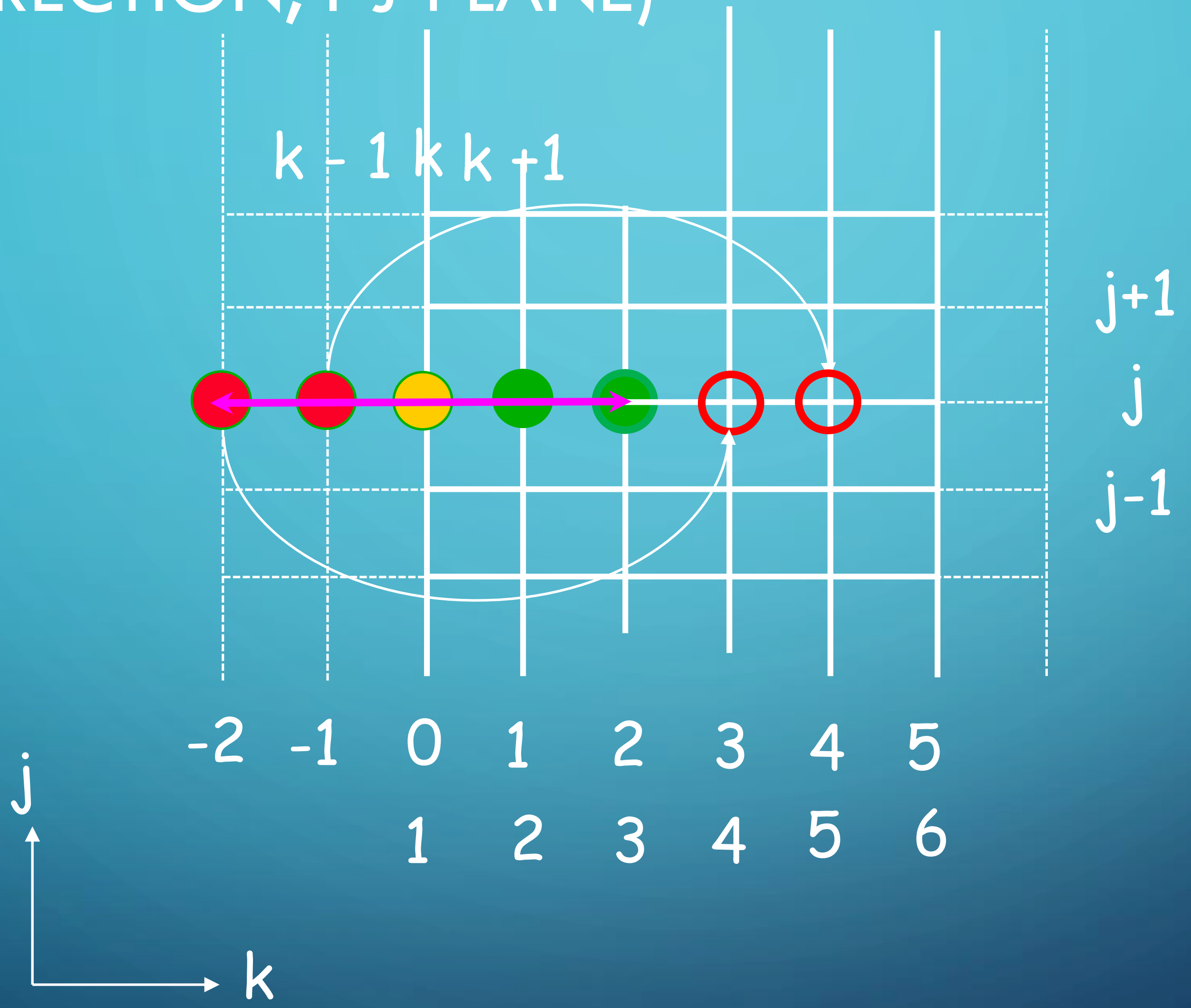
ORTHOGONAL CARTESIAN VS. GENERALIZED COORDINATES



PERIODICITY
(K-DIRECTION, J-K PLANE)



PERIODICITY
(K-DIRECTION, I-J PLANE)



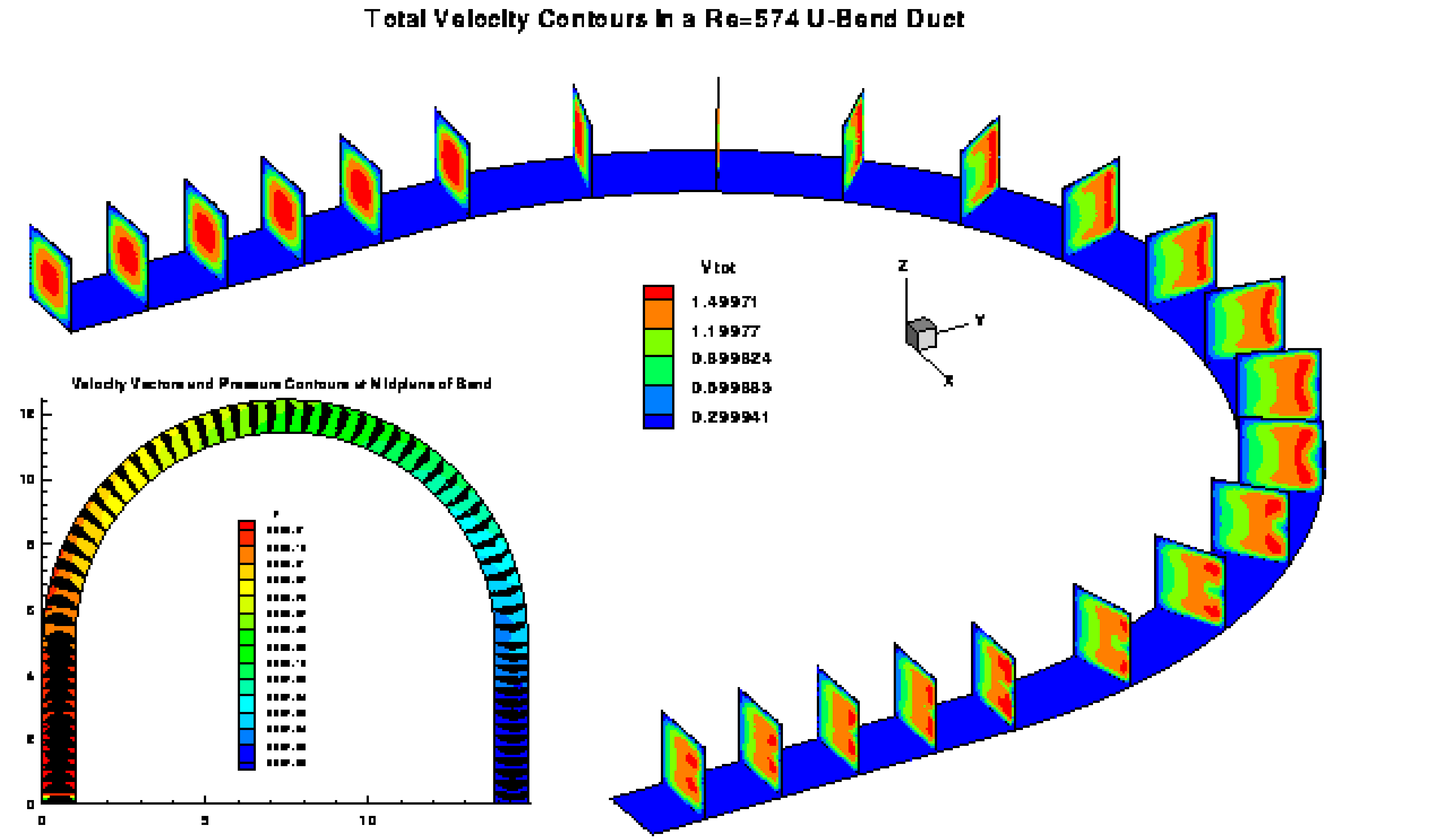
SPECIFICS OF THE „TBD” TOKEN DISPERSED PHASE MODEL FOR AEROSOLS AND AQUASOLS (PARTICLES, DROPLETS AND BUBBLES)

FEATURES OF "TBD" TOKEN DISPERSED PHASE MODEL

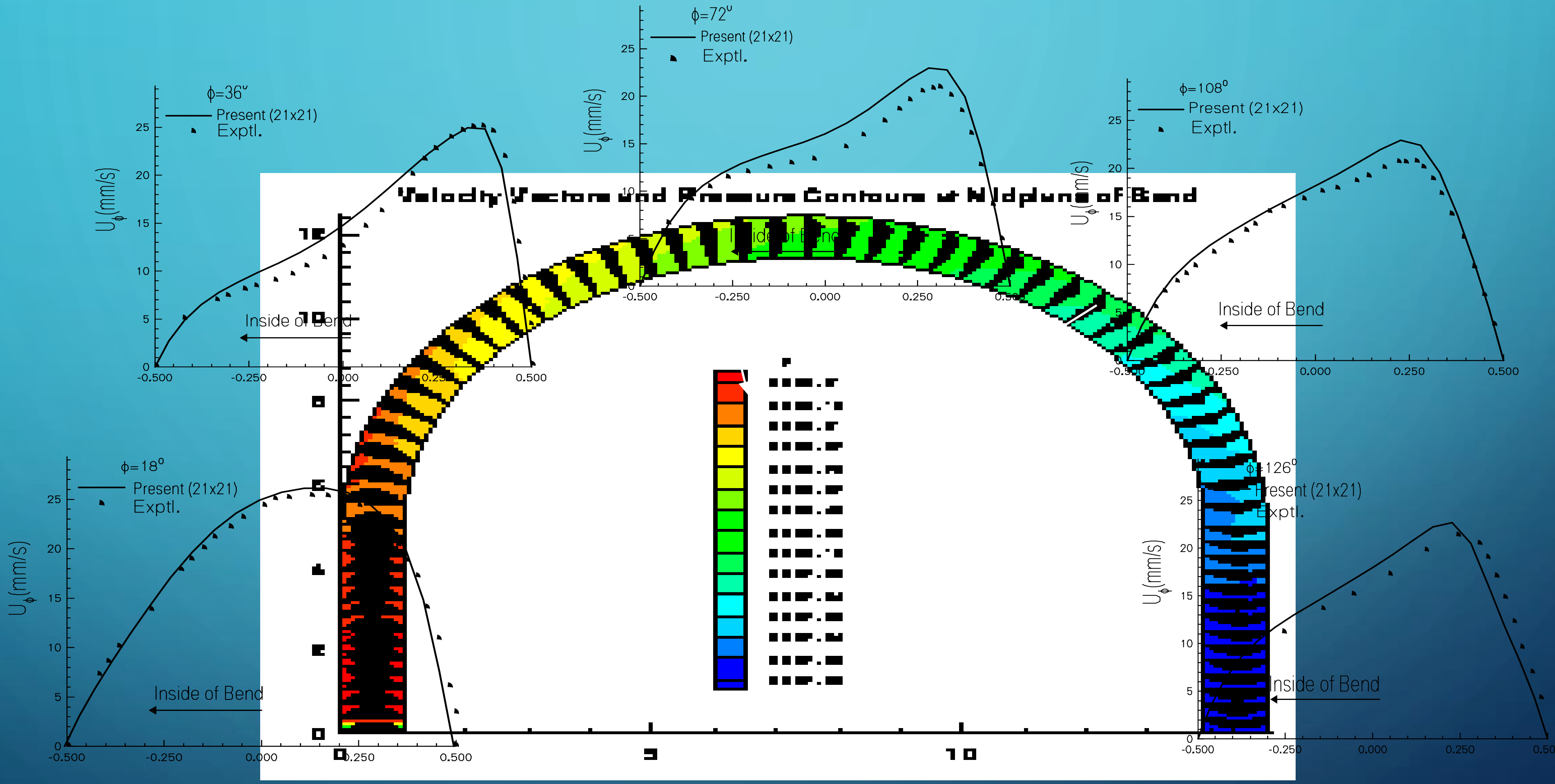
- Stand Alone Code Including Multi-phase Solver and Gridding
- Incompressible/Supersonic
- One/Two/Three-Dimensional
- Internal/External
- Complex Geometries
- Multi-Species with chemical reaction
- Detailed particle transport (convection, diffusion, thermophoresis)
- Detailed particle dynamics (nucleation, condensation, reaction)
- Polydisperse aerosols from nanometer to mm size
- Submodels for various aerosol synthesis phenomena
- Laminar/Turbulent (Flow/Species/Aerosol)
- Strong 3-Way Coupled Flow/Chemical Species/Particles,Bubbles
- Accurate
- Robust

SOME EXAMPLES AND VALIDATION OF THE BULK FLOW SOLVER

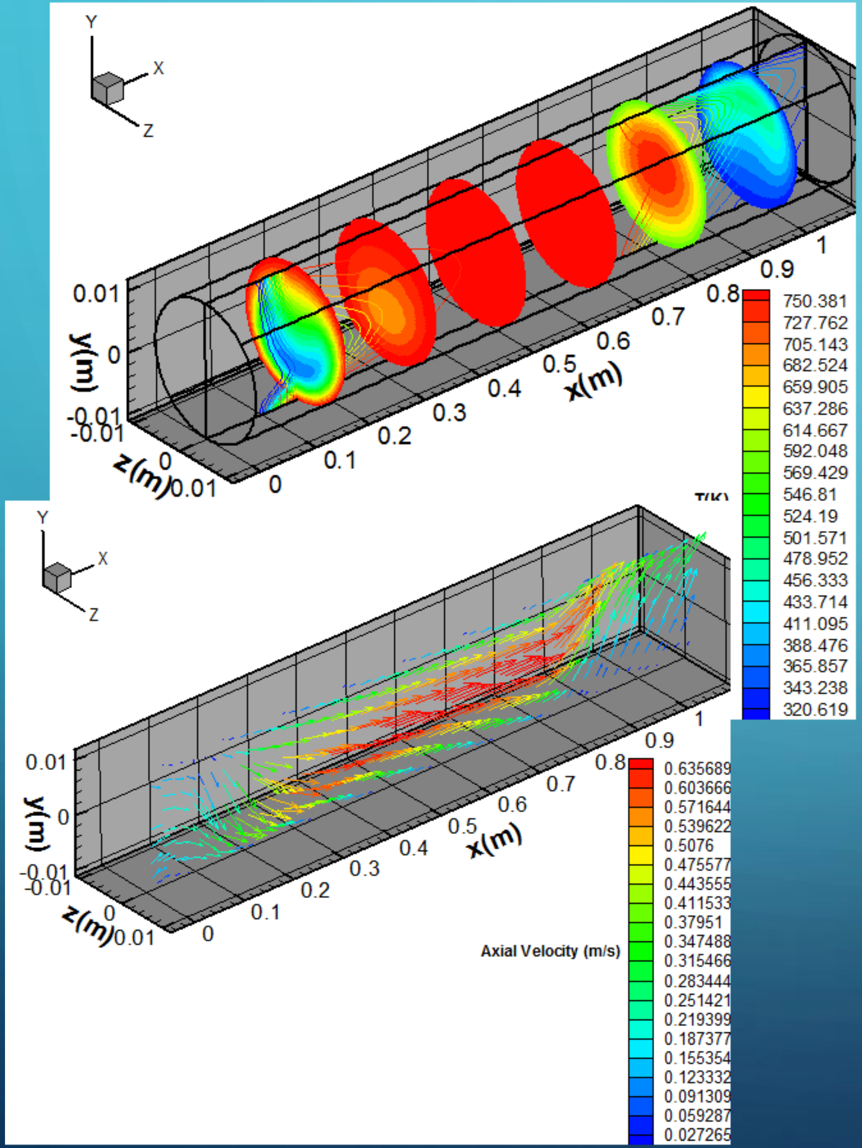
INCOMPRESSIBLE (MACH = 0) FLOW IN A 180 DEGREE TURNAROUND DUCT

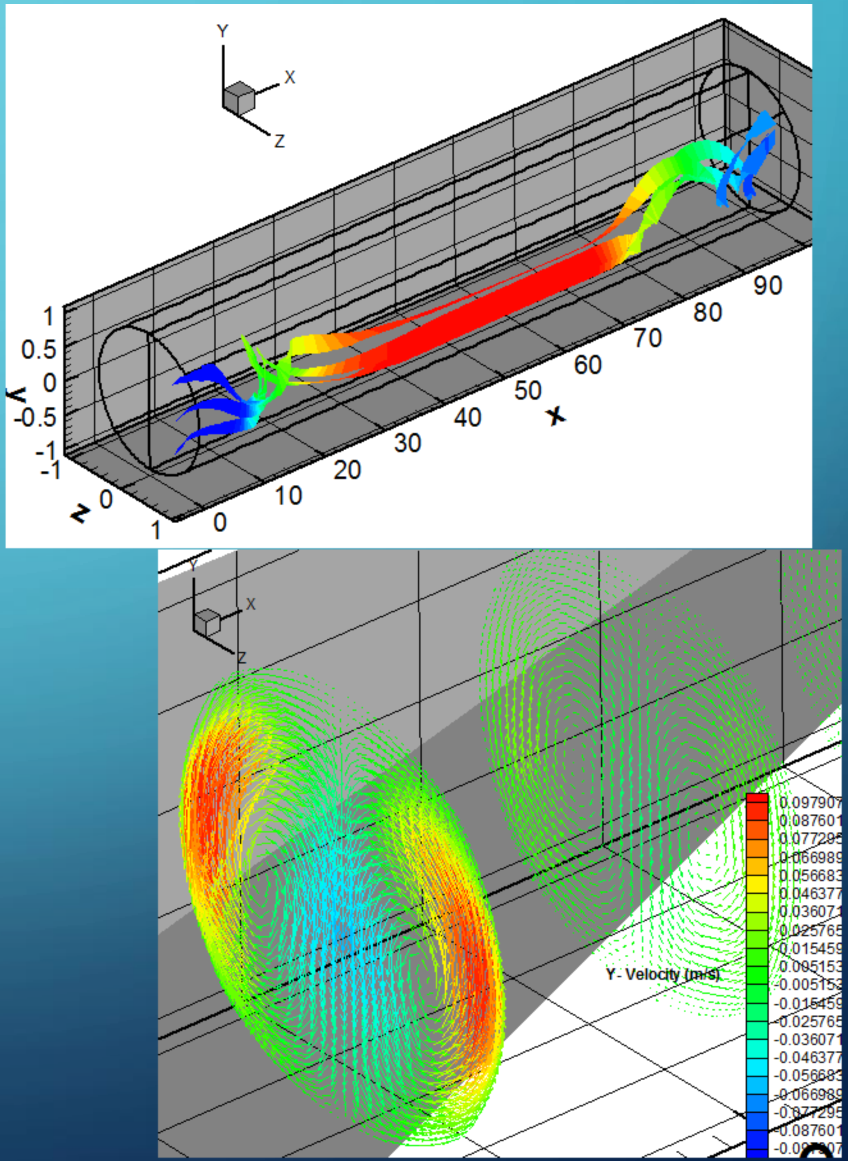


INCOMPRESSIBLE (MACH = 0) FLOW IN A 180 DEGREE TURNAROUND DUCT

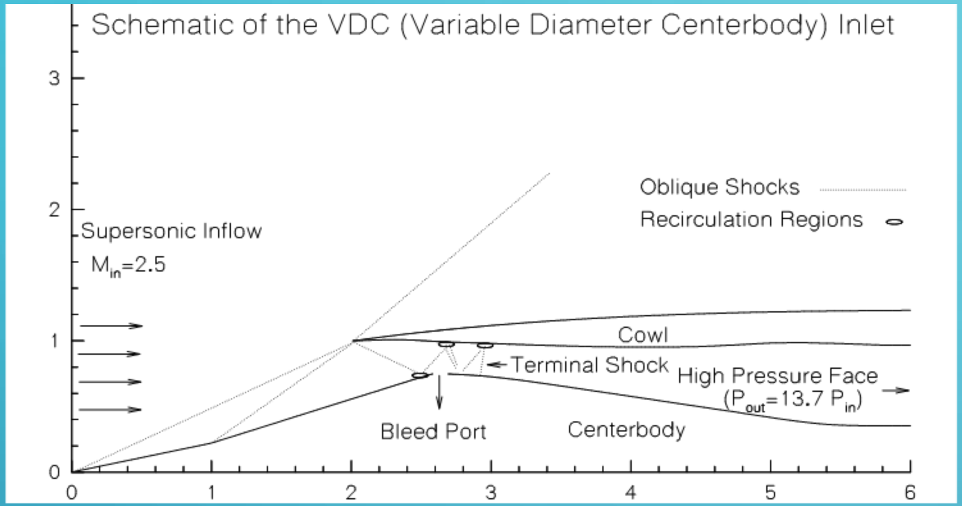


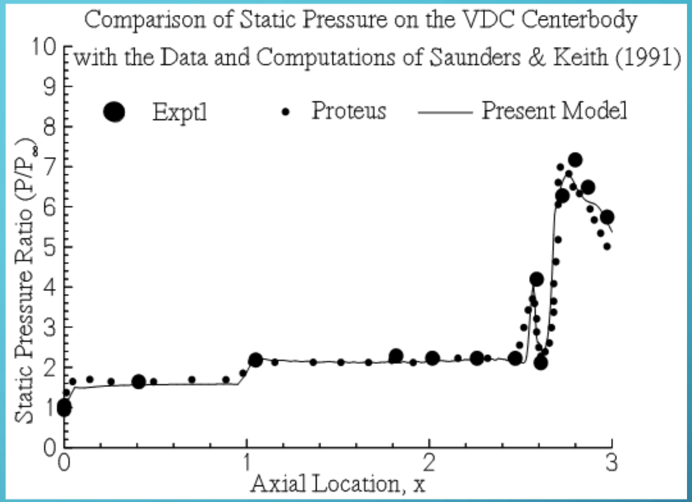
FLOW AND TEMPERATURE IN A HORIZONTAL MICROPARTICLE FURNACE REACTOR

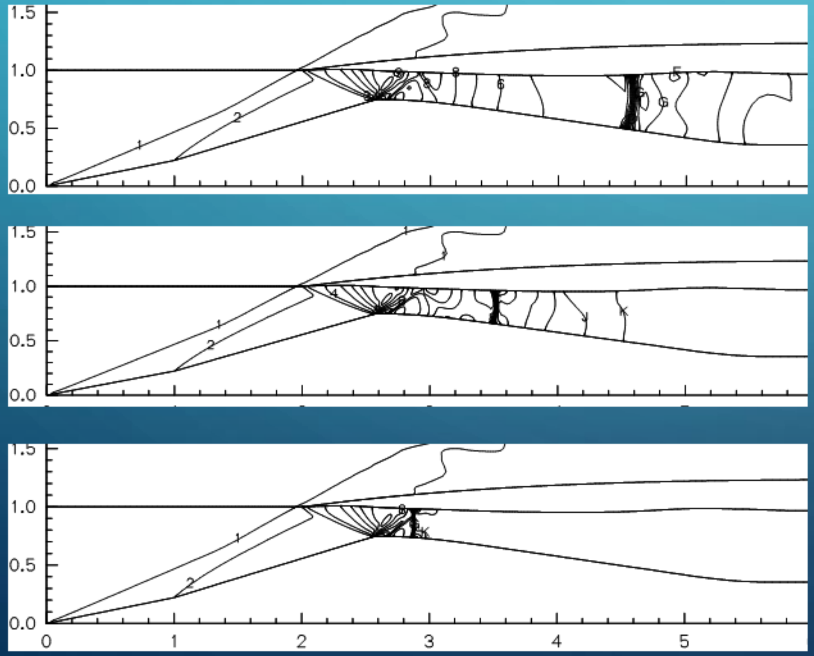


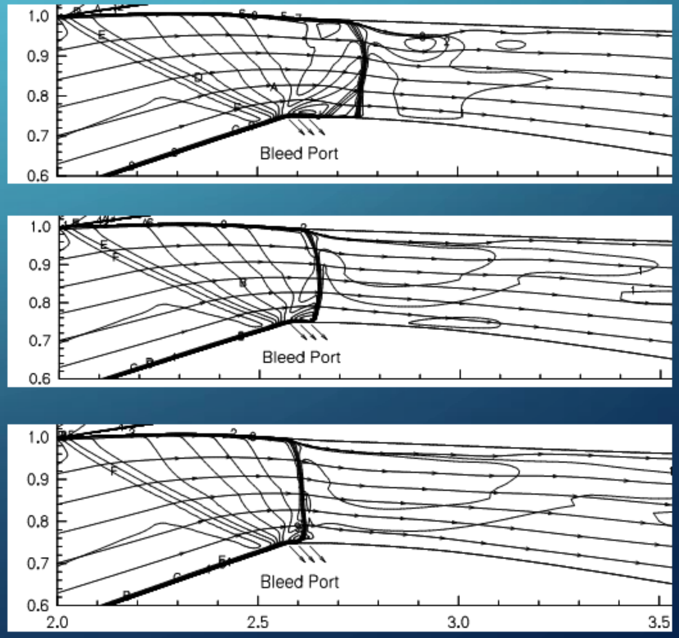


TRANSONIC FLOW IN A SUPERSONIC (MACH 2.5) TURBINE INLET



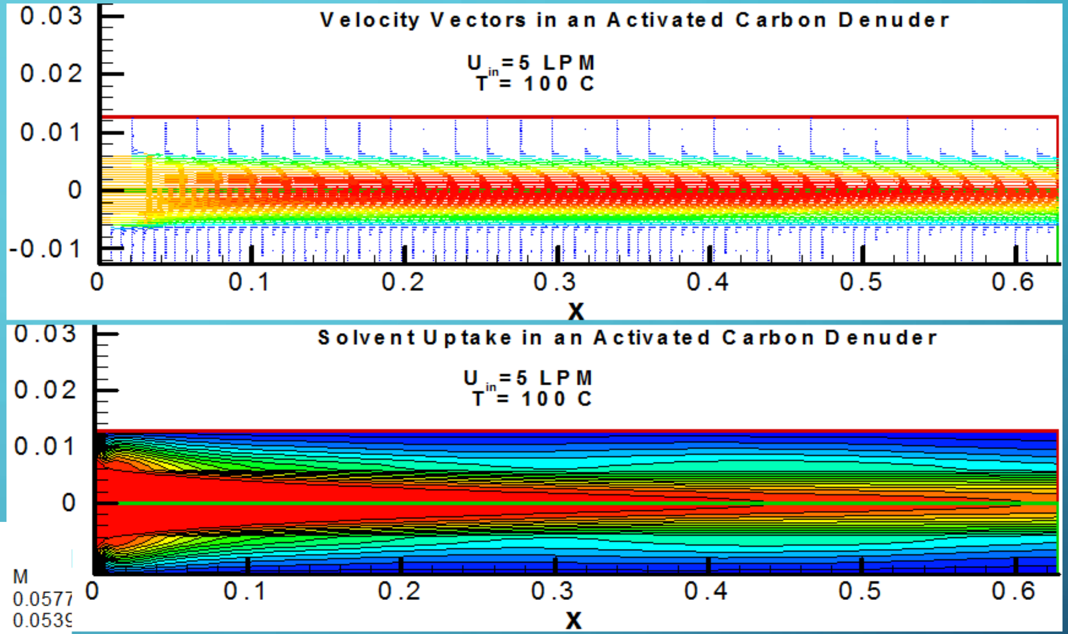


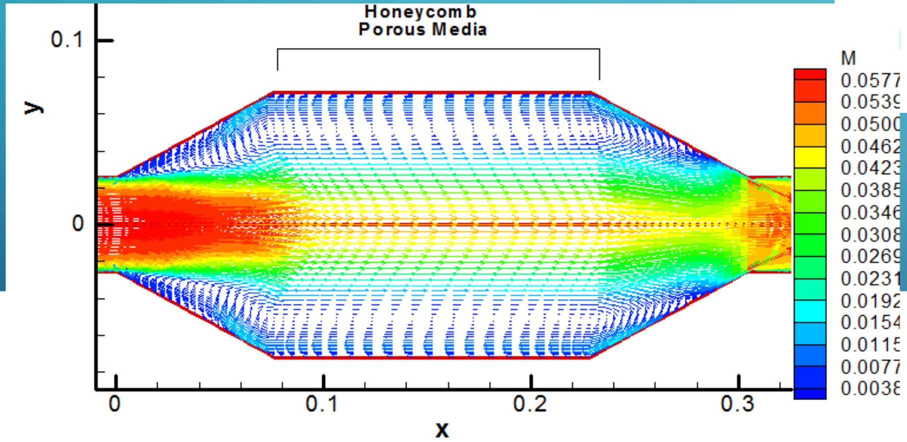


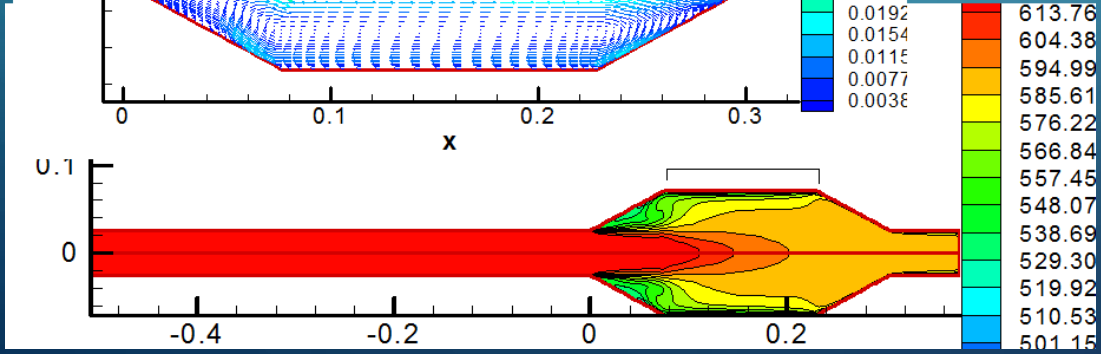


FLOW IN POROUS MEDIA

Solvent Uptake in an Activated Carbon Denuder →





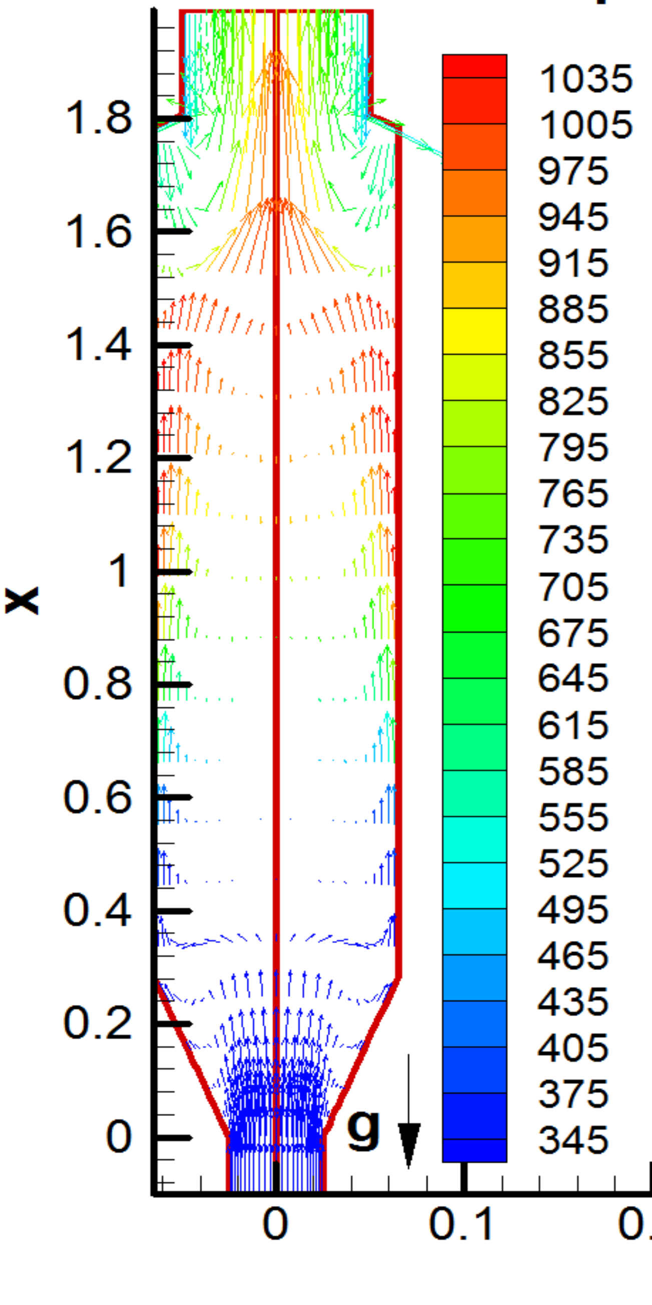


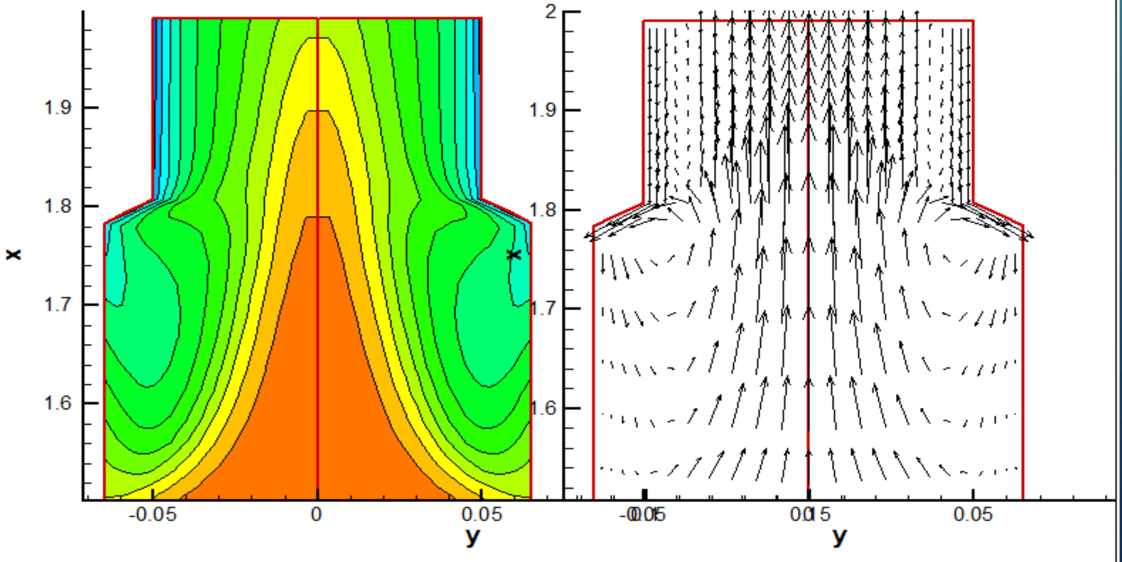
← Cooled Flow in a Diesel Particle Trap

Pilot Scale TiO2 Spray Calcination Reactor Temperature Contours Along the Center Plane (Flow from Bottom to Top)

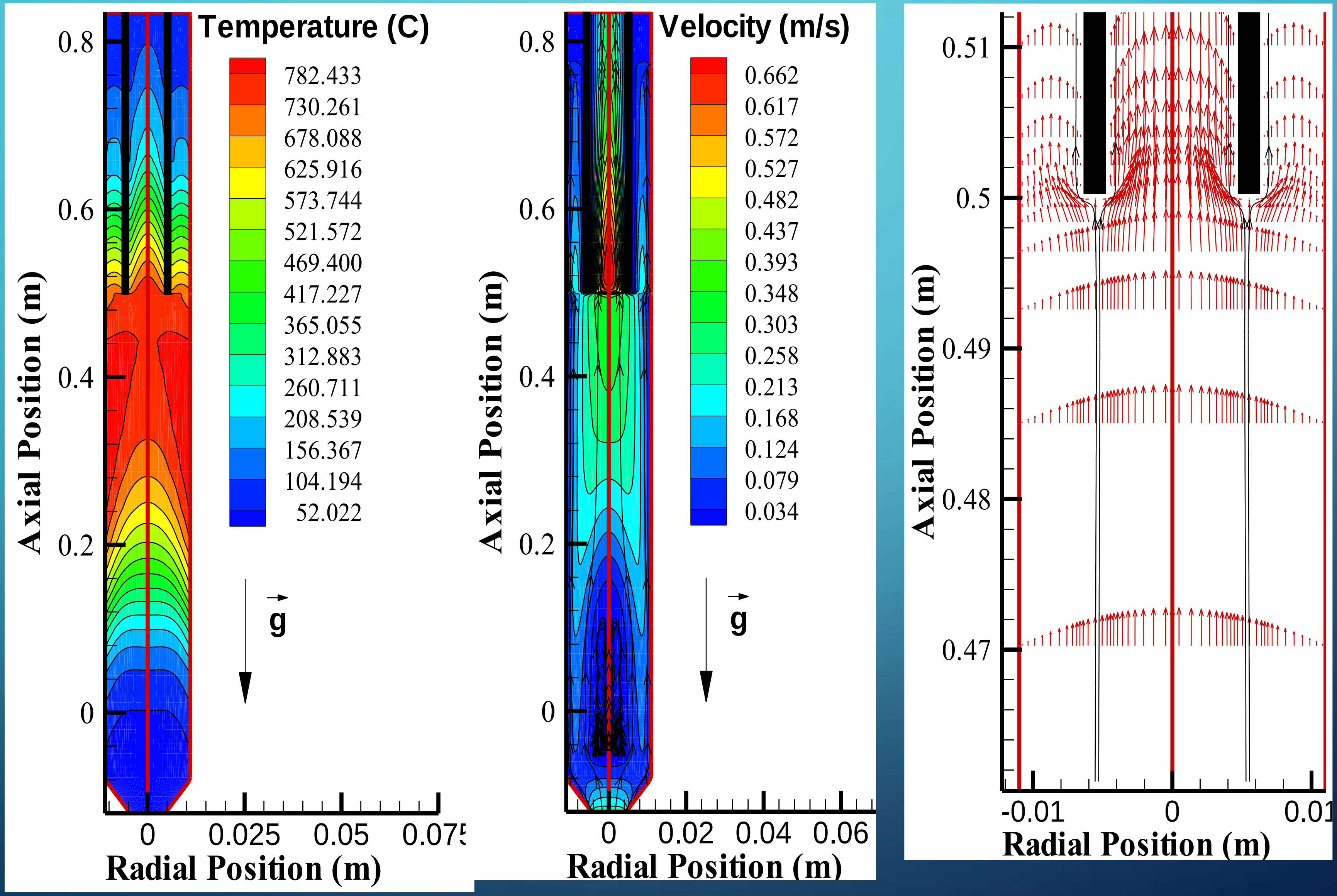
Peak Wall Temperature = 1040 K
Inflow Mass Flow Rate = 36 NL/min
Inflow Velocity = 0.306 m/s
Inlet Diameter = 5 cm
Reactor Diameter = 13 cm
Outlet Diameter = 10 cm

Note: Radial Direction Stretched by a Factor of 3.

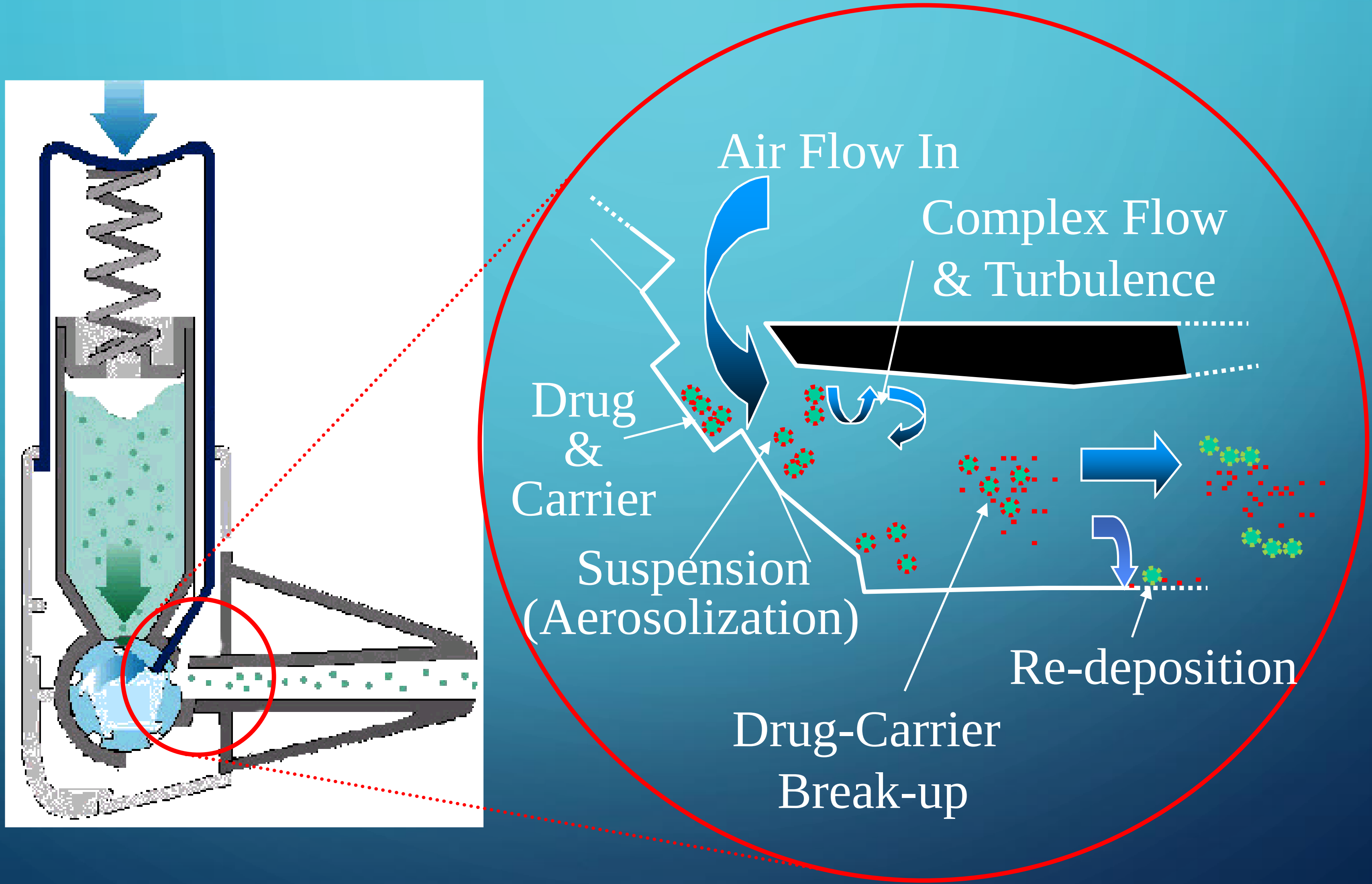




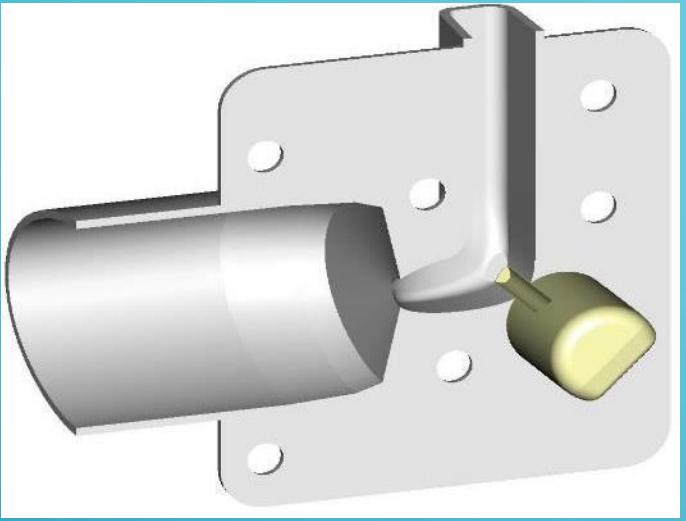
Outlet Flow Control in a Synthesis Reactor

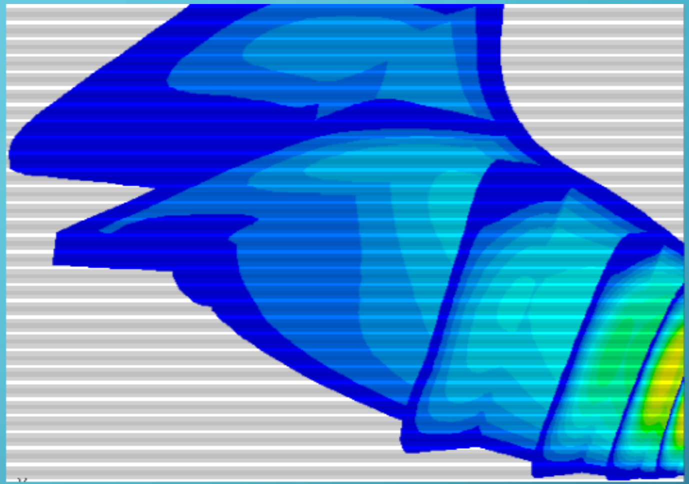


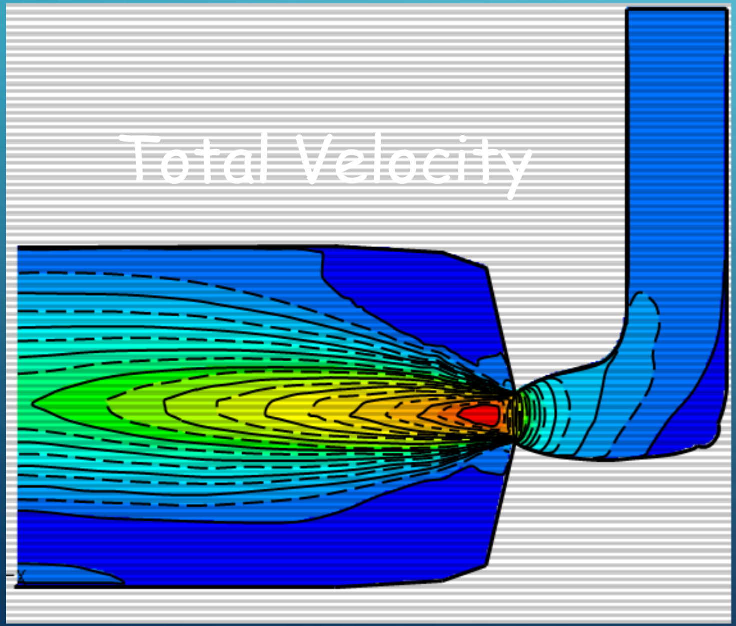
SCHEMATIC OF A TYPICAL INHALATION DRIVEN, MULTIDOSE DRY POWDER INHALER

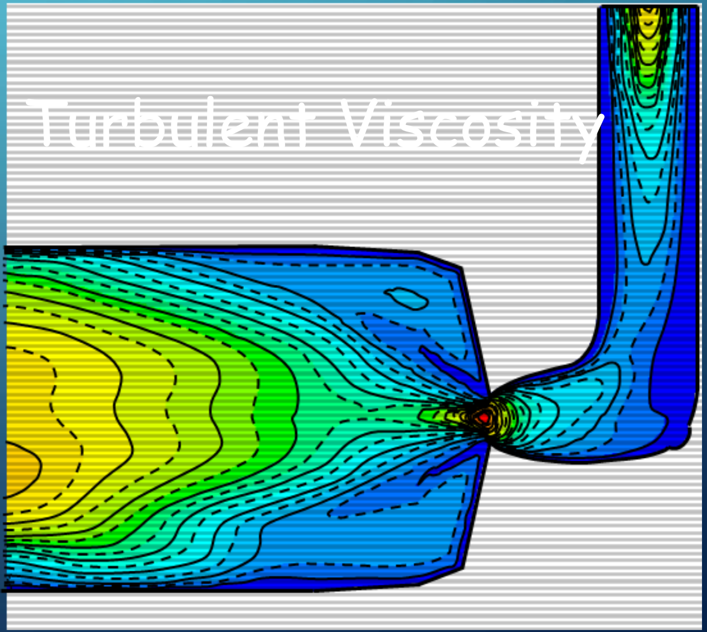


COMPRESSIBLE, TURBULENT, RECIRCULATING FLOW IN A DRY POWDER INHALER

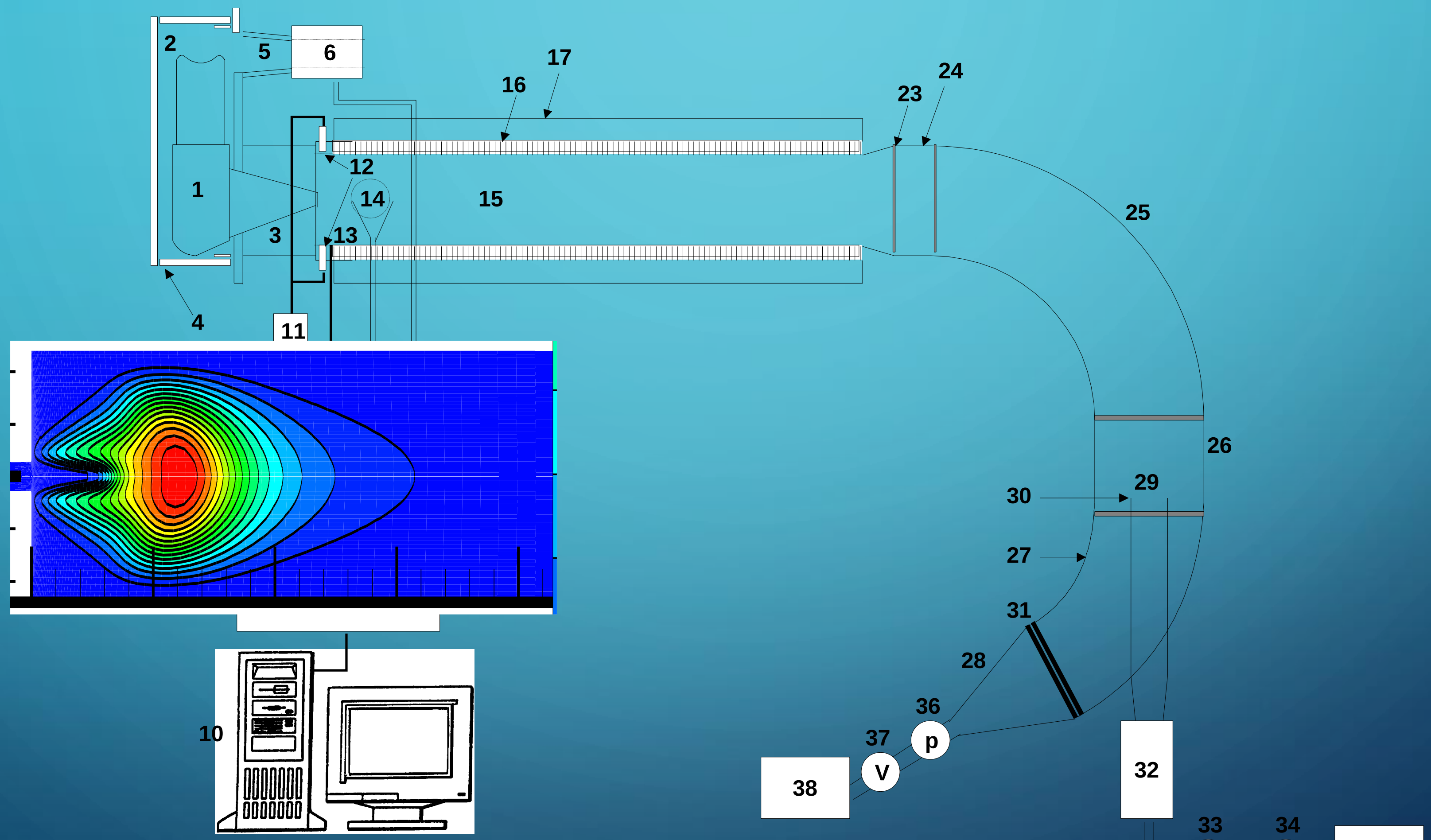




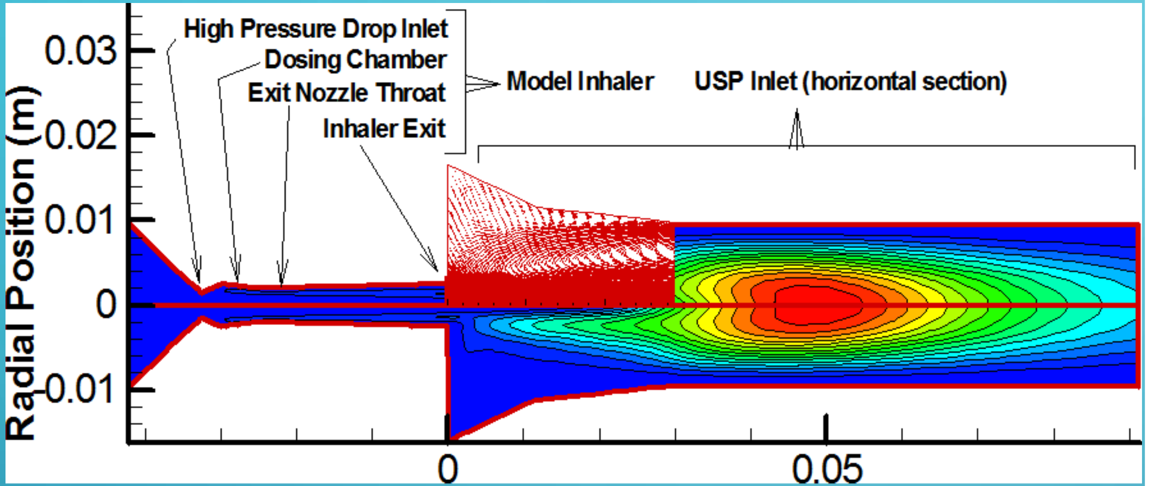




NEXT GENERATION SAMPLING SYSTEM

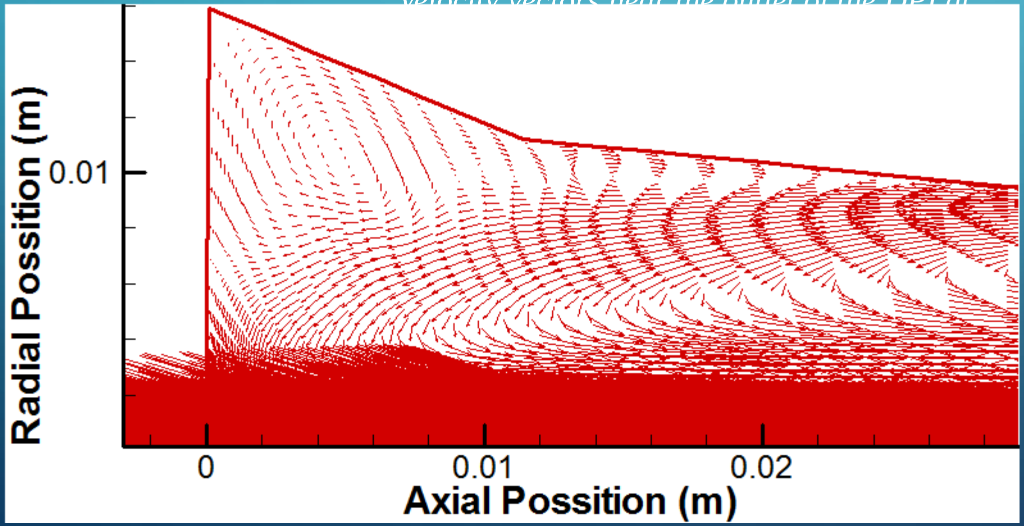


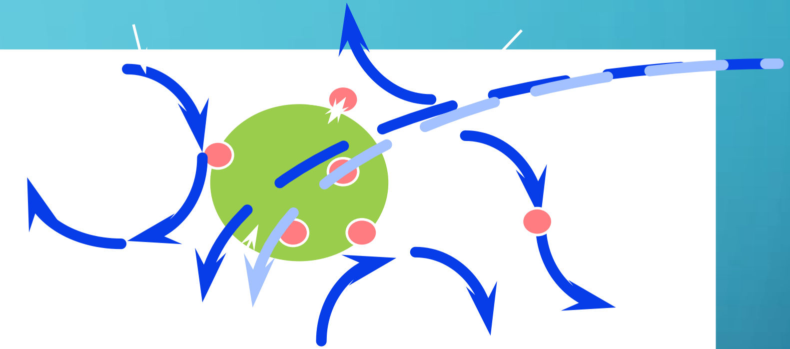
AEROSOLIZATION AND DEAGGLOMERATION IN A MODEL DRY POWDER INHALER & PHARMACOPIA INLET



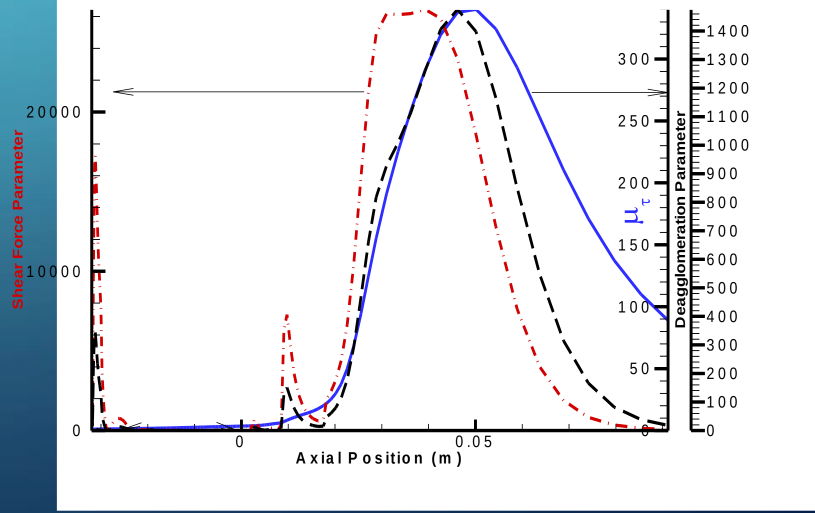
Contours of Non-Dimensional Turbulent Viscosity in model DPI/USP inlet at 60 LPM.

Velocity vectors near the outlet of the DPI at

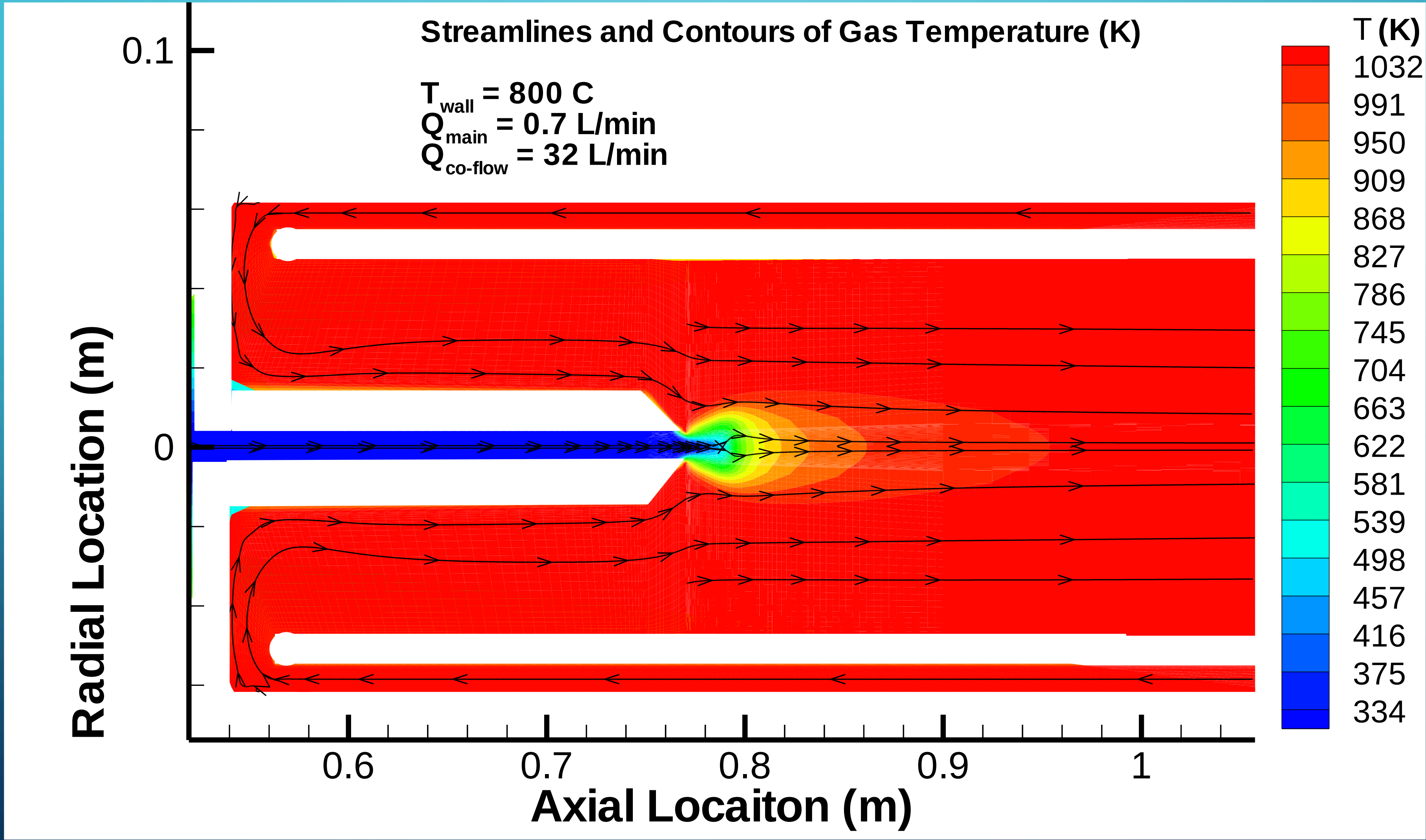




$$P = \mu_t \left(\frac{\partial u_{fi}}{x_j} + \frac{\partial u_{fj}}{x_i} \right) \frac{\partial u_{ffi}}{x_j} - \frac{2}{3} \mu_t \left(\frac{\partial u_{fk}}{x_k} \right)^2$$

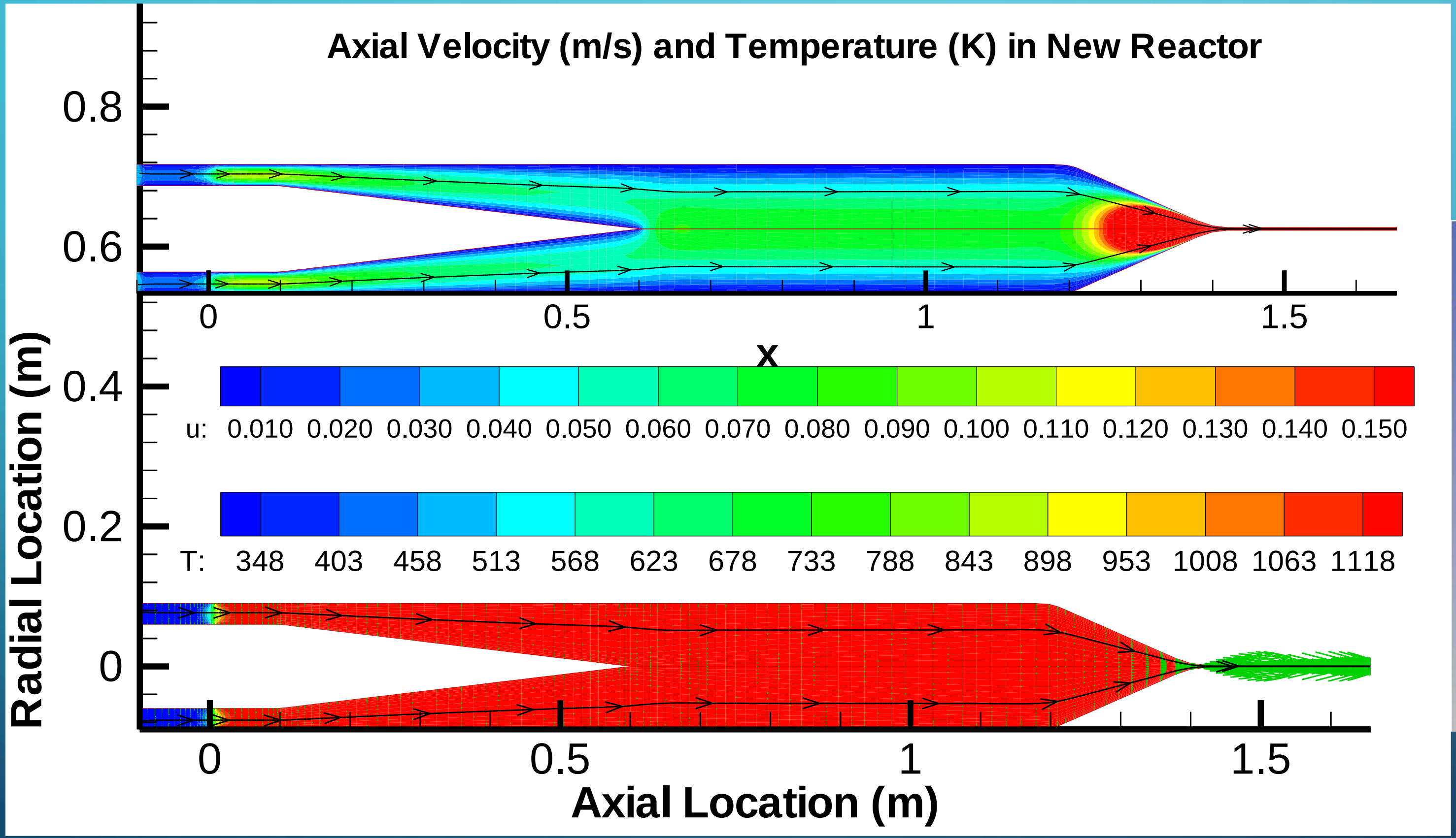


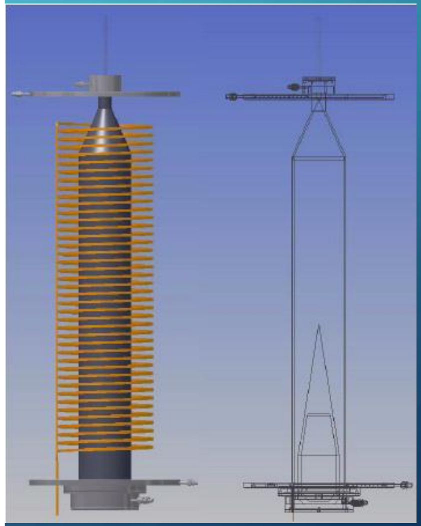
HEAT EXCHANGE IN A NANOPARTICLE REACTOR
"TBD" TOKEN CALCULATION



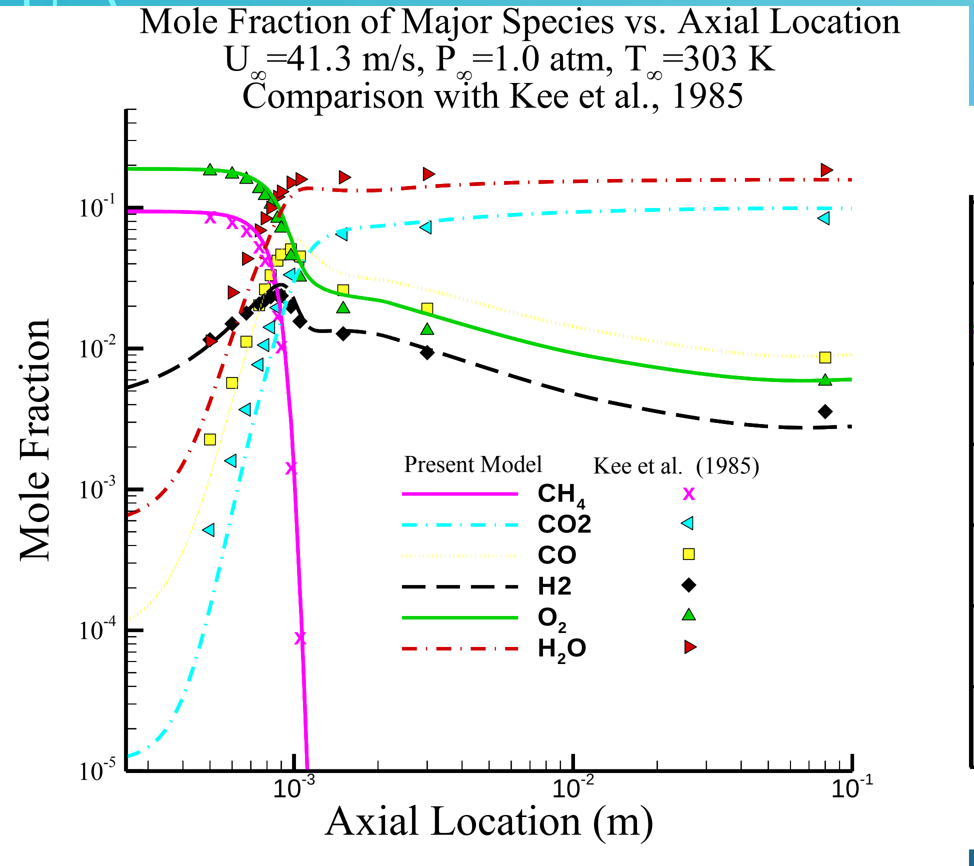
Heat Exchange in a Nanoparticle Reactor

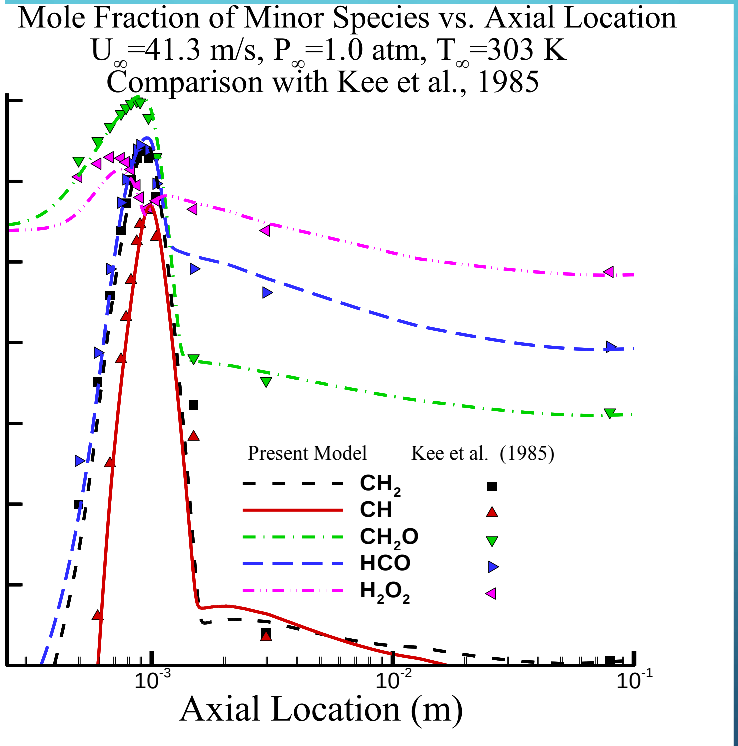
Implemented "TBD" token Calculation & CAD Model



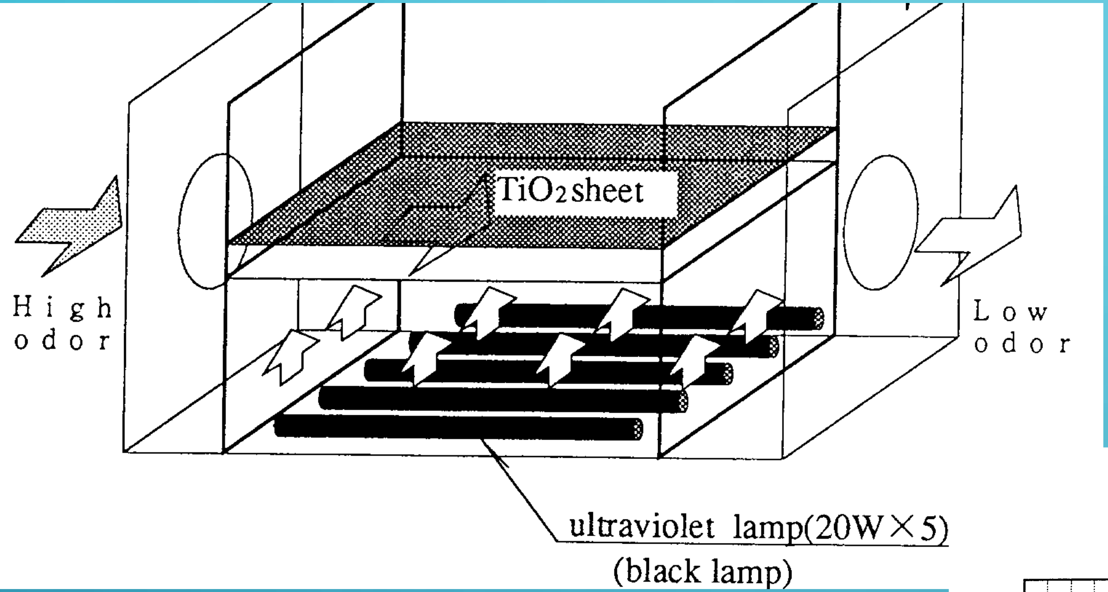


GAS PHASE CHEMICAL KINETICS (METHANE/AIR COMBUSTION)



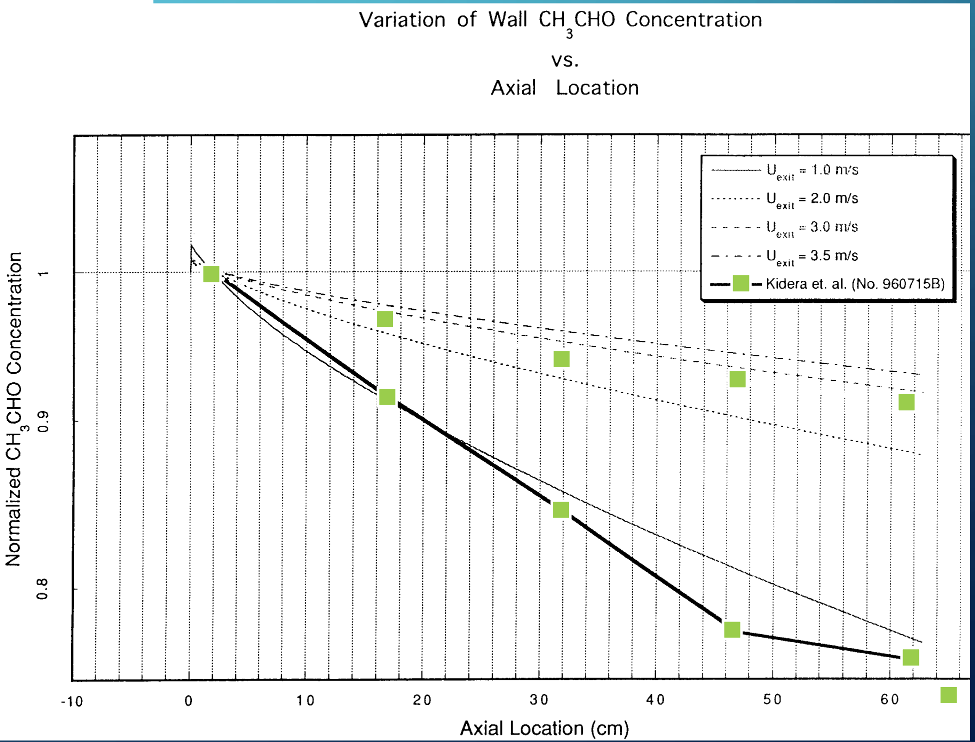


AROMATIC HYDROCARBON PHOTOCATALYSIS IN A PHOTOREACTOR

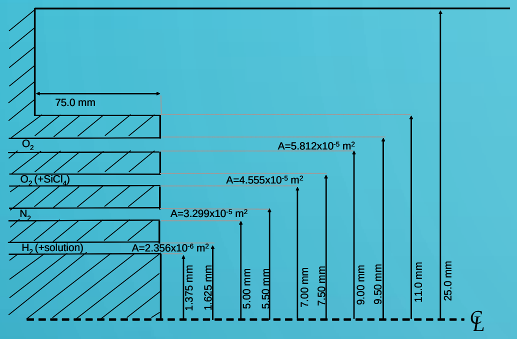


Experimental Apparatus

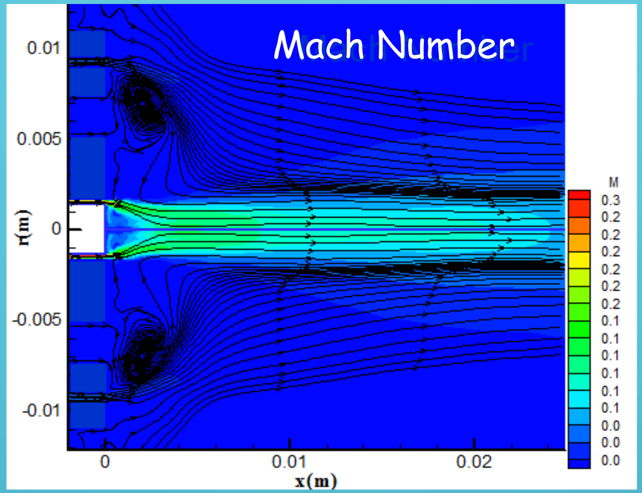
Comparison of Experiment & CFD Results

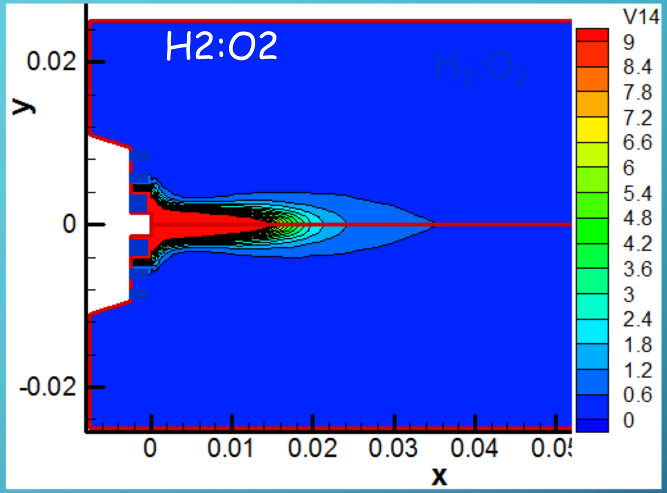


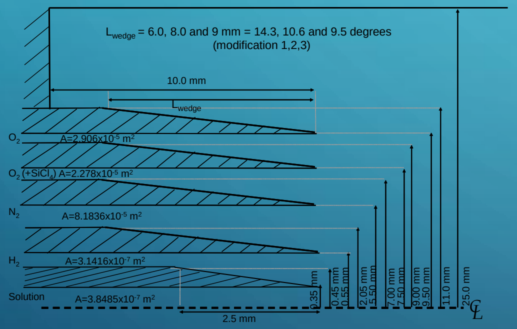
OPTIMIZATION OF A NANOPARTICLE SPRAY COMBUSTION SYNTHESIS AND DEPOSITION NOZZLE



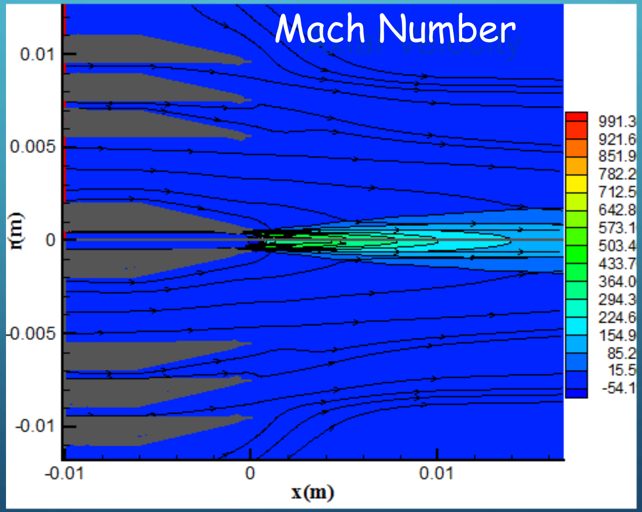
Original Design

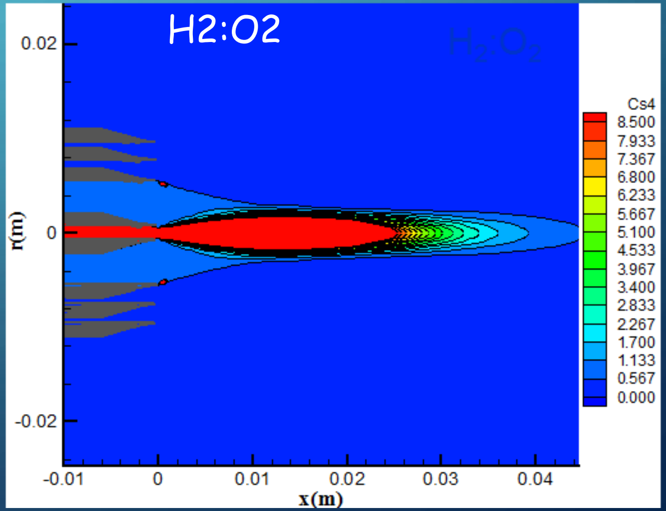






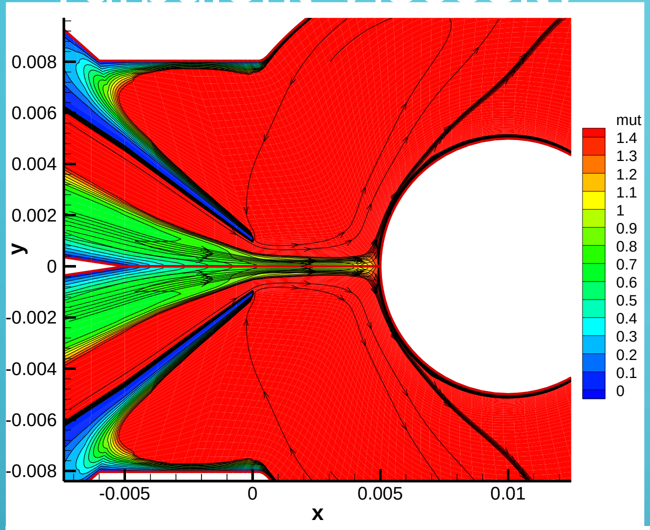
Optimized Design



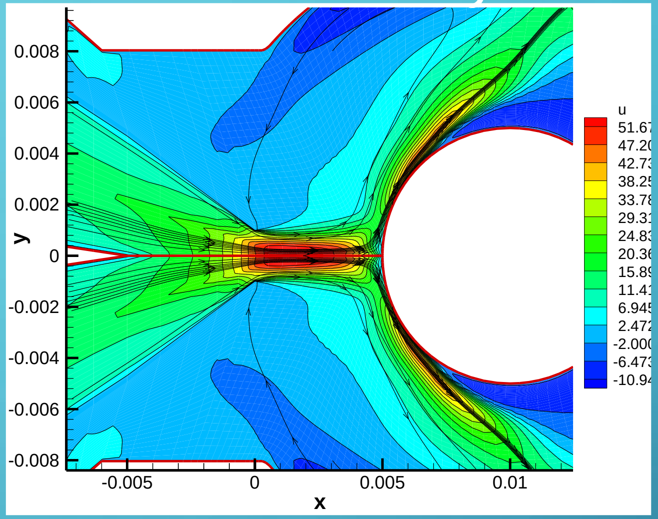


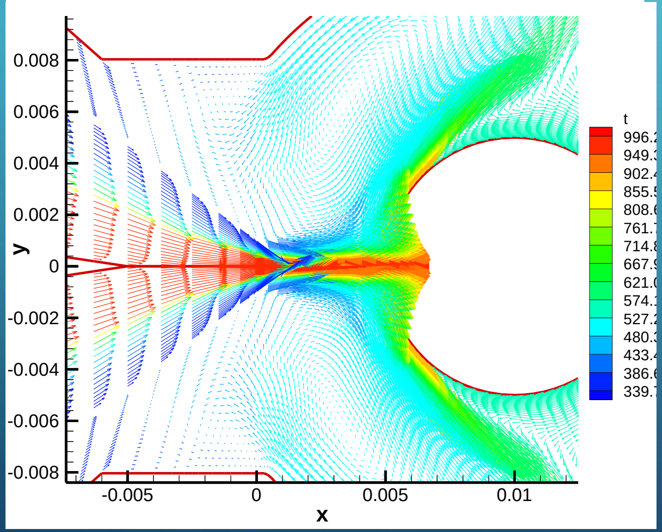
DESIGN OF A MICROPARTICLE DEPOSITION SYSTEM

Turbulent Viscosity

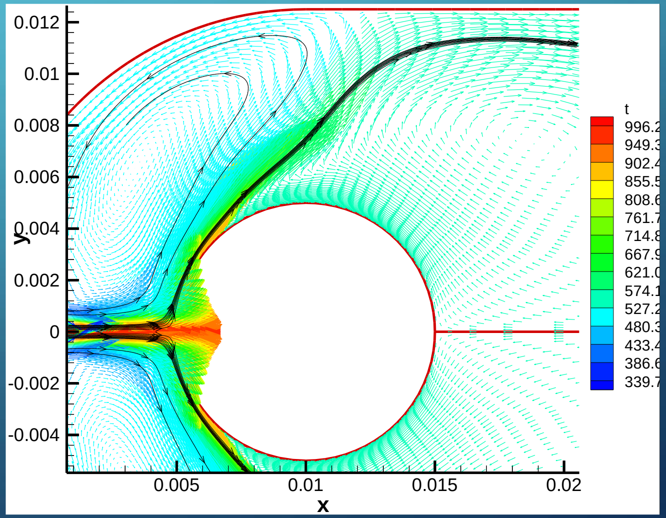


x-Velocity





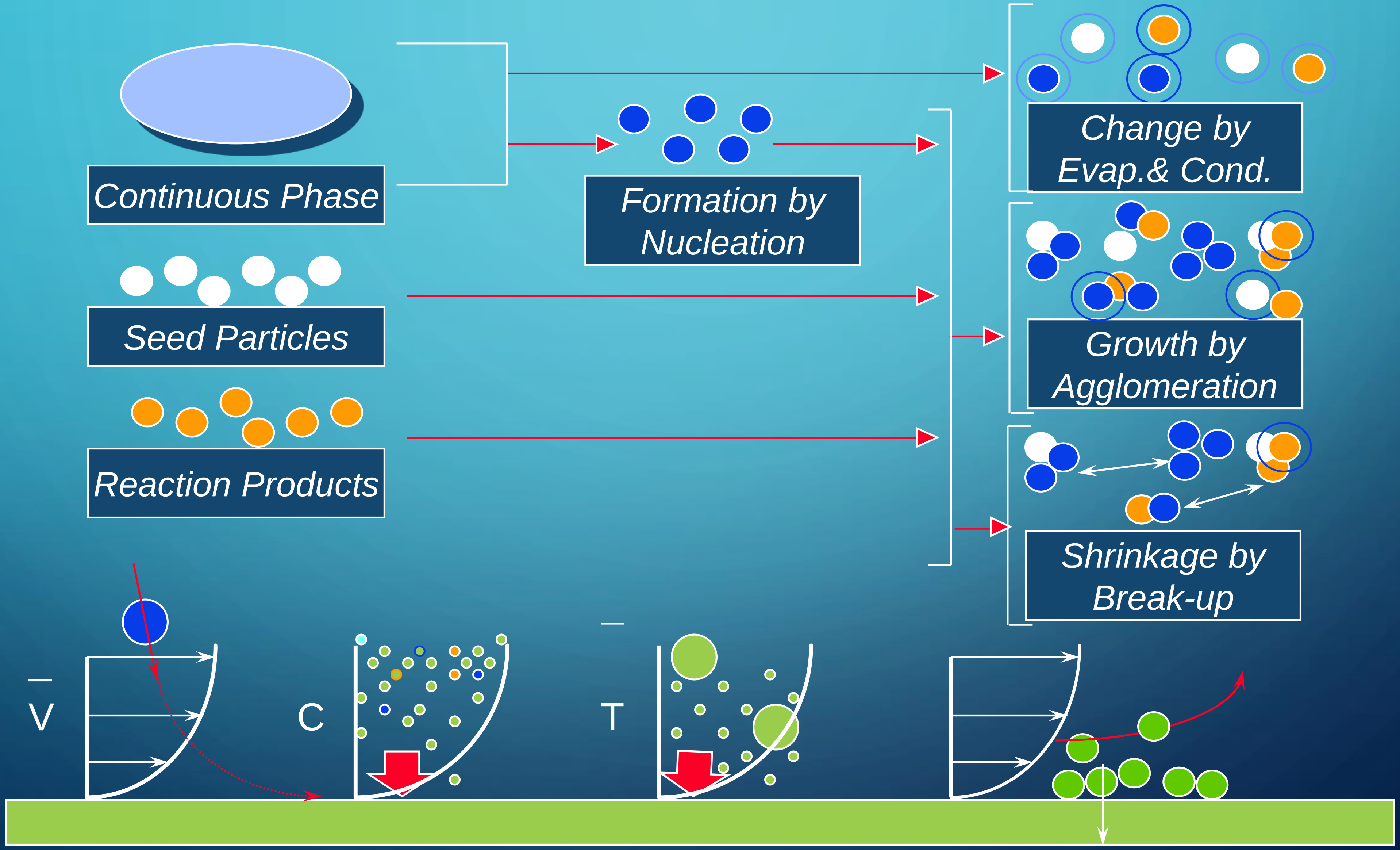
Temperature



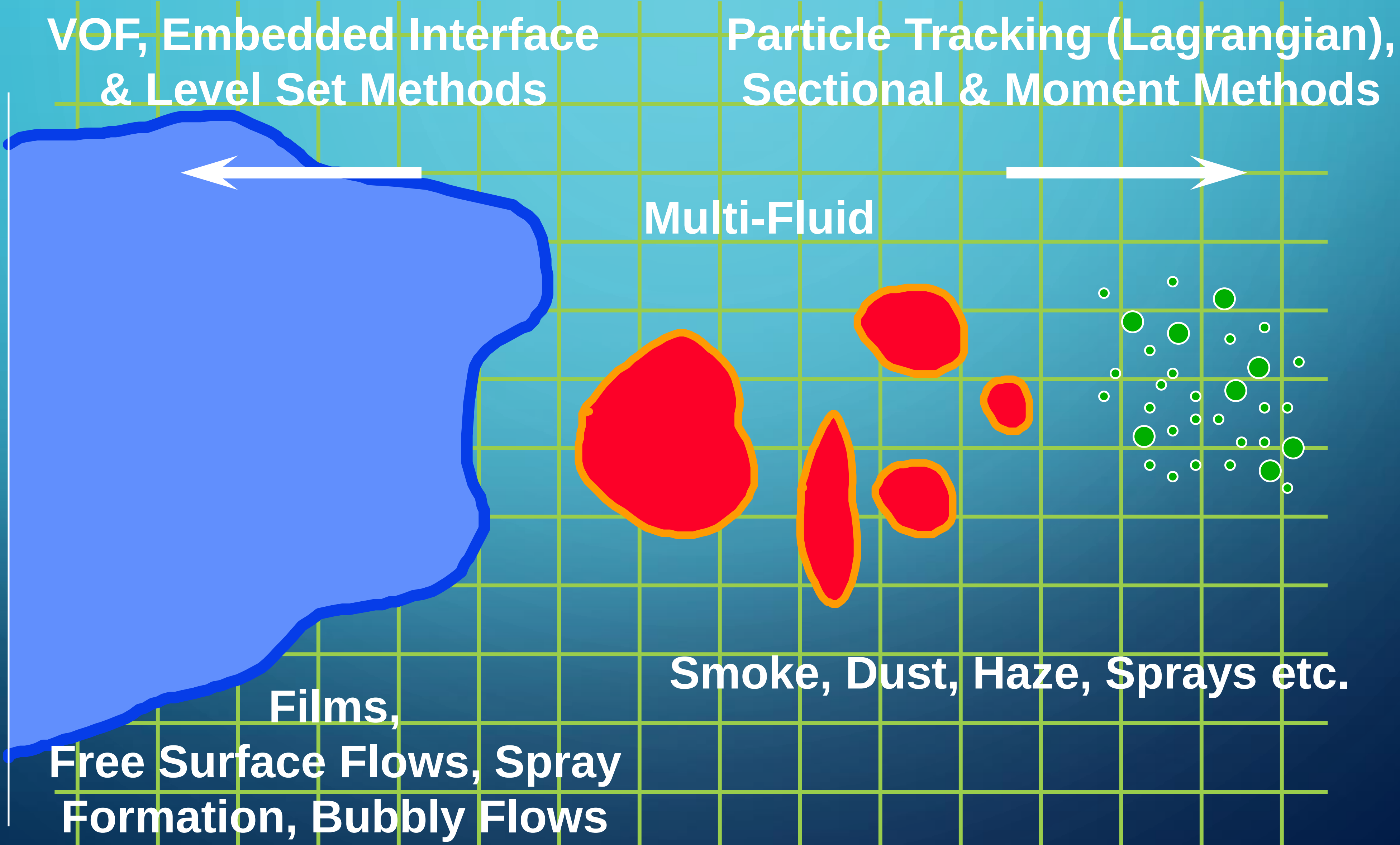
Temperature

THE DISPERSED PHASE MODEL FOR MULTI-PHASE FLOW

TYPES OF PARTICLE/DROPLET/BUBBLE DYNAMICS AND TRANSPORT PROCESSES



SCHEMATIC OF GRID SCALE OF DISPERSED PHASE PROCESSES OF INTEREST



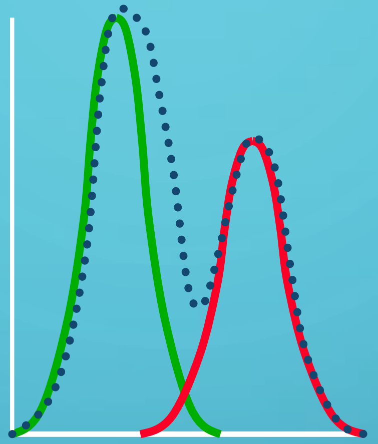
WHEN IS AN EULERIAN FORMULATION OK?

- When any particle having a given state (composition, liquid fraction, temperature …) can be substituted for any other particle having the same state
- When particle history is unimportant
  - e.g. it doesn't matter if a water droplet was formed 4 billion years ago or 1 second ago … it has the same properties)
- When the flow doesn't allow multiple histories in the same physical location
  - Recirculation
  - Non-convective Particle Transport
- When there are many particles

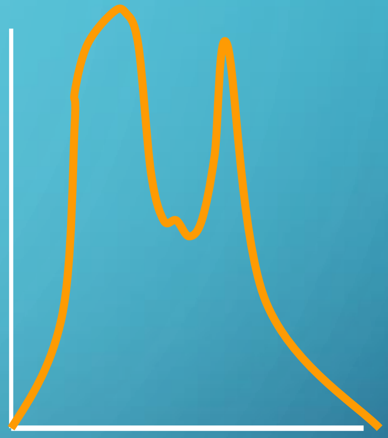
REPRESENTATIONS OF PARTICLE SIZE DISTRIBUTIONS AMENABLE TO EULERIAN SOLUTIONS IN CFD

1) Monodisperse

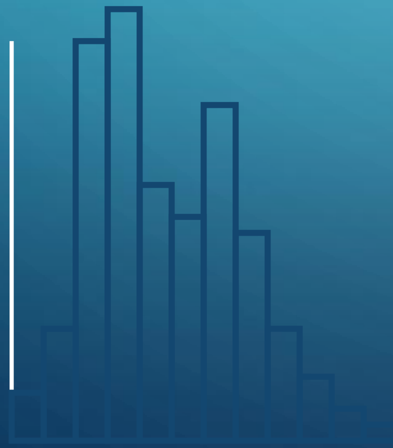
2) Modal (Assumed Dist.)



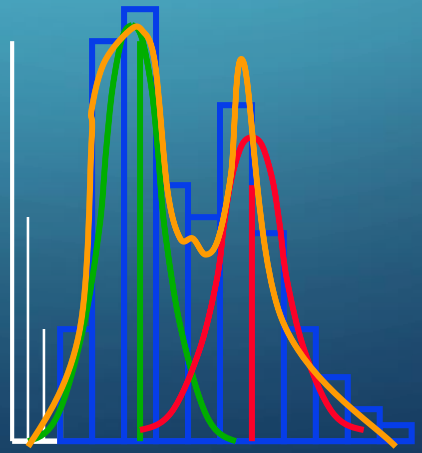
3) Spline/QMOM



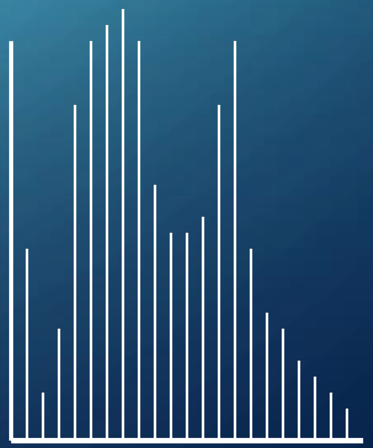
4) Sectional



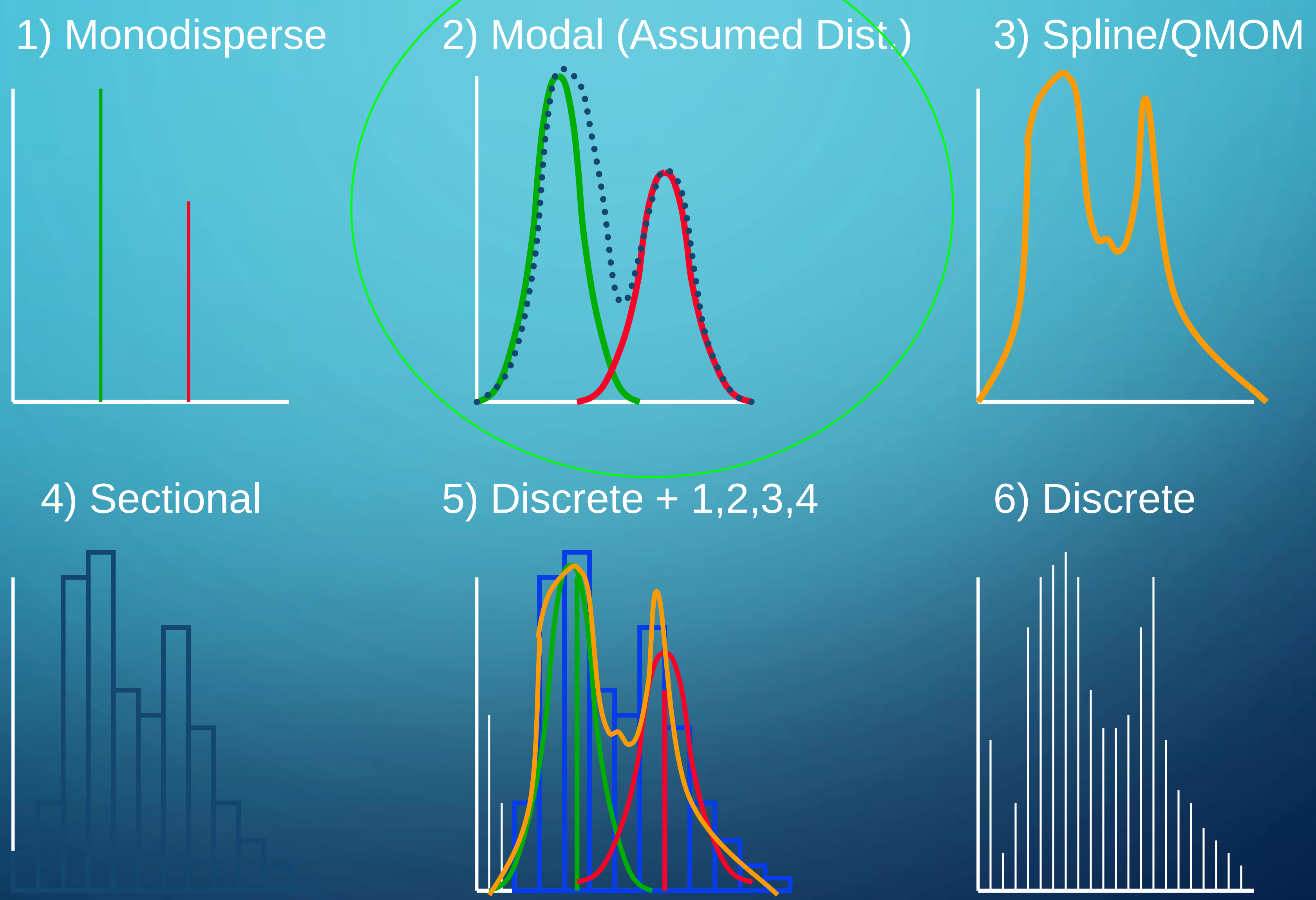
5) Discrete + 1,2,3,4



6) Discrete



REPRESENTATIONS OF PARTICLE SIZE DISTRIBUTIONS AMENABLE TO EULERIAN SOLUTIONS IN CFD

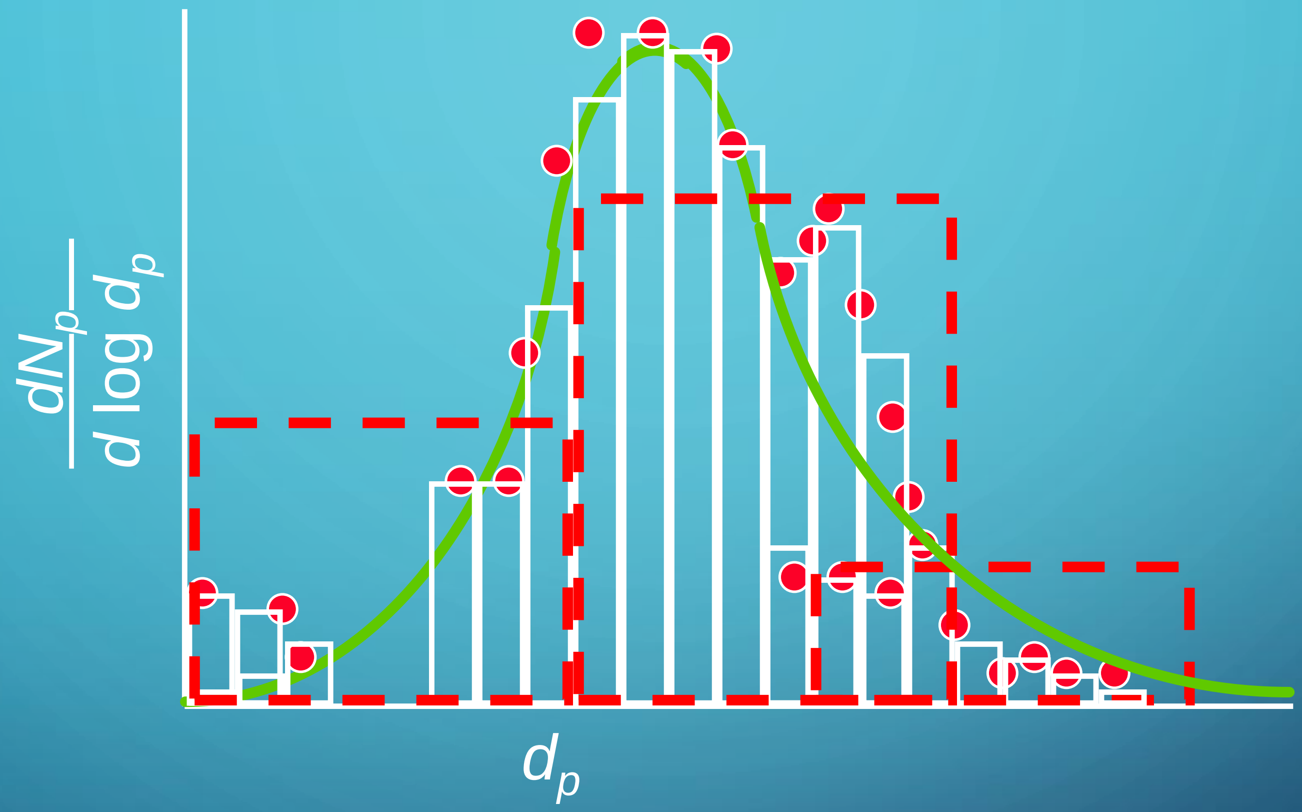


MODEL MOMENTS OF AN ASSUMED SIZE DISTRIBUTION

- Method
  - Assume a statistically large number of particles per volume
  - Treat each moment of an assumed particle size distribution as a transportable ”species” in an Eulerian reference frame
- Advantages
  - First Moment is essentially a species conservation equation
  - No numerical diffusion
  - Small computational resources

    ($6 + n_s + 3$ equations)
- Disadvantages
  - Limited to the assumed distribution
  - Individual particles do not have individual histories
- A great deal of information is retained at a dramatically reduced computational expense

COMPUTATION COST VS. ACCURACY FOR EULERIAN LOGNORMAL & SECTIONAL MODELS



●	Actual Distribution	
green line	Unimodal Lognormal	(3 eqns)
white line	General Sectional with 24 bins	(24 eqns)
red dashed line	General Sectional with 3 bins	(3 eqns)

COMPUTATION COST VS. ACCURACY FOR EULERIAN LOGNORMAL & SECTIONAL MODELS

●	Actual Distribution	
green line	Unimodal Lognormal	(3 eqns)
white line	General Sectional with 24 bins	(24 eqns)
red dashed line	General Sectional with 3 bins	(3 eqns)

ASSUMPTIONS OF THE MOMENT MODEL

- Aerosol/Aquasol Volume Distribution is Lognormal.
- Particles/Droplets/Bubbles are Spherical
  - Use of basic kinetic theory
  - Use of a single parameter for particle/droplet/bubble size

$$n(v) = \frac{N_j}{3\sqrt{2\pi}v \ln \sigma_g} \exp\left\{-\frac{\ln^2(v/v_g)}{18\ln^2 \sigma_g}\right\}$$

$N_j(M_0)$ σ_g v_g

PROBLEM FORMULATION

- Moment form of the GDE (Polydisperse)

$$\int_0^\infty \frac{\partial n_p(v_p)}{\partial t} v_p^k dv_p + \nabla \cdot \left(\int_0^\infty n_p(v_p) v_p^k \mathbf{U}_p dv_p \right)$$

$$= \int_0^\infty (Source\ Term) v_p^k dv_p$$

$$M_k = \int_0^\infty n(v) v^k dv$$

$M_0 \approx$ Number Concentration of Particles

$M_1 \approx$ Volume Concentration of Particles

$M_2 \approx$ Light Scattering Intensity due to Particles

$$v_g = \frac{M_1^2}{M_0^{1.5} M_2^{0.5}} \qquad \ln^2 \sigma = \frac{1}{9} \ln\left(\frac{M_0 M_2}{M_1^2} \right)$$

PARTICLE/DROPLET/BUBBLE VELOCITY EQUATIONS AND MOMENTUM COUPLING

$$\mathbf{U}_{pk} = \mathbf{U}_f + \mathbf{U}_{Dk} + \mathbf{U}_{Ik} + \mathbf{U}_{Tk}$$

$$\mathbf{U}_{pk} = \mathbf{U}_f - \frac{1}{Sc_k Re}\left(\nabla ln(n)\right) - St_k(\mathbf{U}_{pk} \cdot \nabla)\mathbf{U}_{pk} - \frac{K_{Tk}}{Re}\nabla T$$

$$Sc_0 = 1\Big/\left(A_3 \mathrm{v}_g^{-1/3} \, exp\left(0.5 \, ln^2 \, \sigma\right) + A_4 \mathrm{v}_g^{-2/3} \, exp(2 \, ln^2 \, \sigma)\right)$$

$$Sc_1 = 1\Big/\left(A_3 \mathrm{v}_g^{-1/3} \, exp\left(-2.5 \, ln^2 \, \sigma\right) + A_4 \mathrm{v}_g^{-2/3} \, exp(-4 \, ln^2 \, \sigma)\right)$$

$$Sc_2 = 1\Big/\left(A_3 \mathrm{v}_g^{-1/3} \, exp\left(5.5 \, ln^2 \, \sigma\right) + A_4 \mathrm{v}_g^{-2/3} \, exp(-10 \, ln^2 \, \sigma)\right)$$

$$St_0 = A_1 \, \mathrm{v}_g^{2/3} \, exp\left(2 \, ln^2 \, \sigma\right) + A_2 \, \mathrm{v}_g^{1/3} \, exp\left(0.5 \, ln^2 \, \sigma\right)$$

$$St_1 = A_1 \, \mathrm{v}_g^{2/3} \, exp\left(8 \, ln^2 \, \sigma\right) + A_2 \, \mathrm{v}_g^{1/3} \, exp\left(3.5 \, ln^2 \, \sigma\right)$$

$$St_2 = A_1 \, \mathrm{v}_g^{2/3} \, exp\left(14 \, ln^2 \, \sigma\right) + A_2 \, \mathrm{v}_g^{1/3} \, exp\left(6.5 \, ln^2 \, \sigma\right)$$

LOGNORMAL MOMENT MODEL

- Lognormal Moment form of GDE (i.t.o. M_k)

$$\frac{\partial (M_k)}{\partial t} + \nabla(\mathbf{V} M_k) - \nabla \cdot \left(\frac{1}{Sc_k \,\mathrm{Re}} \nabla M_k \right) + \nabla \cdot \left\{ M_k \left[St_k (\mathbf{V} \cdot \nabla)\mathbf{V} + \frac{K_t}{\mathrm{Re}\, T} \nabla T \right] \right\}$$

$$= \gamma_k M_k^2 M_{k\infty} t_\infty + \sum_{s=1}^{N_s} \left(\alpha_k (S_s - 1) M_k + \frac{I}{M_{k\infty}} (v^*)^k \right) t_\infty$$

- Species Concentration (Mass Balance) Eq.

$$\nabla \cdot \left[\rho C_s \left(U - \frac{1}{Sc_s \,\mathrm{Re}} \nabla (\ln C_s) \right) \right] = -\frac{I_s k^*}{n_s \tau} - \alpha_{1s} (S_s - 1) M_1$$

TRANSFORMED LOGNORMAL AEROSOL MOMENT MODEL

- Lognormal Moment form of GDE (i. t. o. W_k)

$$\rho\frac{\partial W_k}{\partial t}+\rho\left(\mathbf{V}-\tilde{\mathbf{V}}_{\boldsymbol{k}}\right)\cdot\nabla W_k-e^{-W_k}\nabla\cdot\left(\frac{\rho e^{W_k}}{Sc_k\,\mathrm{Re}}\nabla W_k\right)-\left(1-e^{-W_k}\right)\nabla\cdot\rho\tilde{\mathbf{V}}_{\boldsymbol{k}}$$

$$=\gamma_k\rho^2\left(e^{W_k}-2+e^{-W_k}\right)M_{k\infty}t_\infty+\sum_{s=1}^{N_s}\left(\alpha_k\left(S_s-1\right)\rho\left(1-e^{-W_k}\right)+\frac{Ie^{-W_k}}{M_{k\infty}}\left(v^*\right)^k\right)t_\infty$$

- Where

$$M_k/\rho=e^{W_k}-1\quad or\quad W_k=\ln\left(M_k/\rho+1\right)$$

- Defining Non-Advective Particle Velocity as

$$\tilde{\mathbf{V}}_{\boldsymbol{k}}=\frac{1}{\rho Sc_k\,\mathrm{Re}}\nabla\rho+St_k\left(\mathbf{V}\cdot\nabla\right)\mathbf{V}+\frac{K_t}{\mathrm{Re}\,T}\nabla T=\mathbf{V}_k^D+\mathbf{V}_k^I+\mathbf{V}_k^T$$

FREE MOLECULAR AND CONTINUUM COEFFS

- Coagulation

$$\gamma_0 = \frac{\gamma_0^c \gamma_0^{fm}}{\gamma_0^c + \gamma_0^{fm}} \left(\frac{M_{0\infty} L_\infty}{U_\infty} \right), \quad \gamma_2 = 0, \quad \gamma_2 = \frac{\gamma_2^c \gamma_2^{fm}}{\gamma_2^c + \gamma_2^{fm}} \left(\frac{M_{2\infty} L_\infty}{U_\infty} \right)$$

- Condensation

$$\alpha_{0s} = 0, \quad \alpha_{1s} = \frac{\alpha_{1s}^c \alpha_{1s}^{fm}}{\alpha_{1s}^c + \alpha_{1s}^{fm}} \left(\frac{L_\infty}{U_\infty} \right), \quad \alpha_{2s} = \frac{\alpha_{2s}^c \alpha_{2s}^{fm}}{\alpha_{2s}^c + \alpha_{2s}^{fm}} \left(\frac{L_\infty}{U_\infty} \right)$$

DEFINITION OF MACH # FOR MULTI-PHASE

$$Cp = \sum_{s=1}^{Ns} C_s Cp_s + C_p Cp_p$$

$$\mathrm{MW} = \left(\sum_{s=1}^{\mathrm{Ns}} \rho_s \mathrm{C_s} + \rho_p \mathrm{C}_p \right) \Big/ \sum_{s=1}^{\mathrm{Ns}} \frac{\rho_s \mathrm{C_s}}{\mathrm{MW_s}}$$

$$\gamma = \left(1 - R \, / \, MW \; Cp \right)$$

$$M = \sqrt{\frac{u^{*2} + v^{*2} + w^{*2}}{\gamma \, RT^*}}$$

INTEGRATED PROPERTIES OF THE DISTRIBUTION

- Since the particle transport and dynamics equations are solved in lognormal moment form, integral distribution properties can be calculated from the total flux of moments out of the domain
- The total flux of moment k at station i is

$$\overline{M}_{k,i} = \frac{\sum_{j=1}^{Nj} M_{k,i,j} \rho u_{x,i,j} g_x}{\sum_{j=1}^{Nj} \rho u_{x,i,j} g_x}$$

- Thus the integral geometric mean particle volume and standard deviation of the distribution exiting through as surface are

$$\overline{\mathrm{v}}_g = \frac{\overline{M}_1^2}{\overline{M}_0^{1.5} \overline{M}_2^{0.5}} \qquad \ln^2 \overline{\sigma} = \frac{1}{9} \ln\left(\frac{\overline{M}_0 \overline{M}_2}{\overline{M}_1^2} \right) + \ln^2 \sigma_\infty$$

CONTINUOUS / DISPERSED PHASE COUPLING

- Fully coupled
  - Density, Enthalpy, Cp, Viscosity etc.
- Additive Source Terms
  - Mass / Momentum / Energy
    - Nucleation, Condensation, Chemical Reaction, Transport

$$\Delta m_s = -\frac{I_{Nuc\,s} k_s^{\circ} + I_{Rxn\,s}}{\tau_s} v_{1s} - \alpha_{1s}(S_s - F_s) M_1 + \sum_r \left(\frac{\partial C_s}{\partial t} \right)_r$$

$$\Delta m = \sum_{s=1}^{Ns} \Delta m_s \qquad \Delta\, Momentum = St_1(\mathbf{U}_f - \mathbf{U}_{p,1}) M_1$$

$$\Delta H_t = \sum_{s=1}^{Ns} \left(\left(-\frac{I_{Nuc\,s} k_s^{\circ}}{\tau_s} v_{1s} - \alpha_{1s}(S_s - F_s) M_1 \right) dHV_s - \frac{I_{Rxn\,s}}{\tau_s} v_{1s}\, dH\,R_s \right)$$

WEAK COUPLING VS. STRONG COUPLING OF THE CONTINUOUS AND DISPERSED PHASES

- For Weak Coupling, the Bulk Fluid equations take the general form

$$\frac{D(\rho_f \varphi_i)}{Dt} + \nabla \cdot (\rho_f \boldsymbol{U} \varphi_i) = \nabla \cdot (\Gamma_{fi}(\varphi_i, \varphi_j, \ldots) \nabla \varphi_i) + S_i(\varphi_i, \varphi_j, \ldots)$$

$$\varphi = 1, \boldsymbol{U}, H_{tf}$$

- where

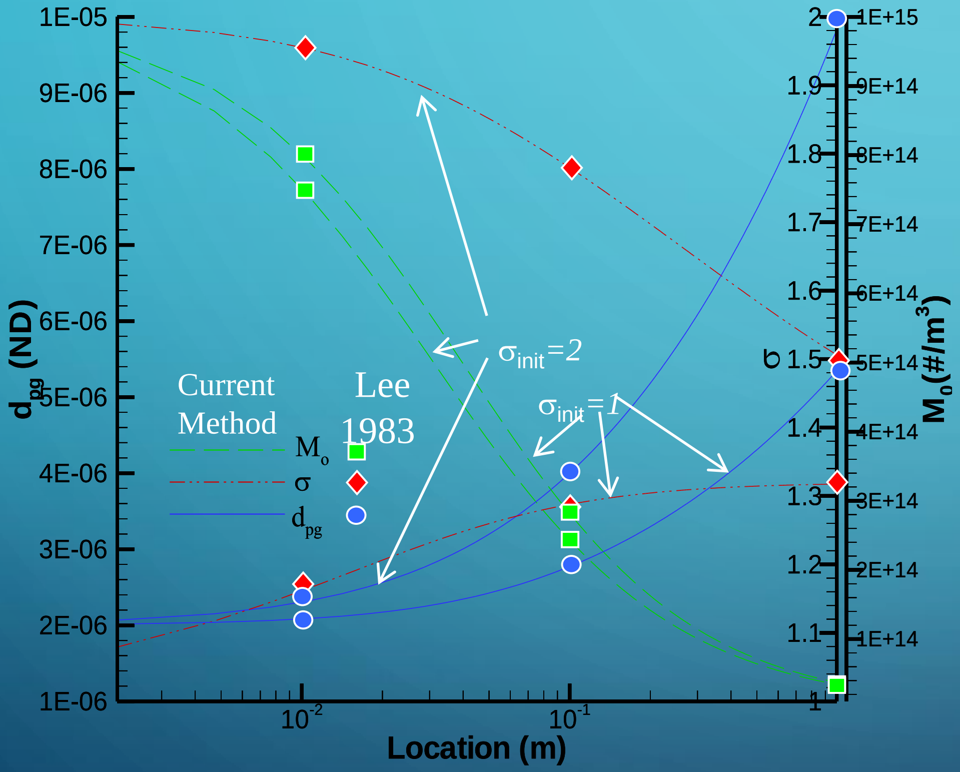
- For Strong Coupling, the Bulk Aerosol equations become

$$\frac{D(\rho_a \varphi_i)}{Dt} + \nabla \cdot (\rho_a \boldsymbol{U} \varphi_i) = \nabla \cdot (\Gamma_{ai}(\varphi_i, \varphi_j, \ldots) \nabla \varphi_i)$$

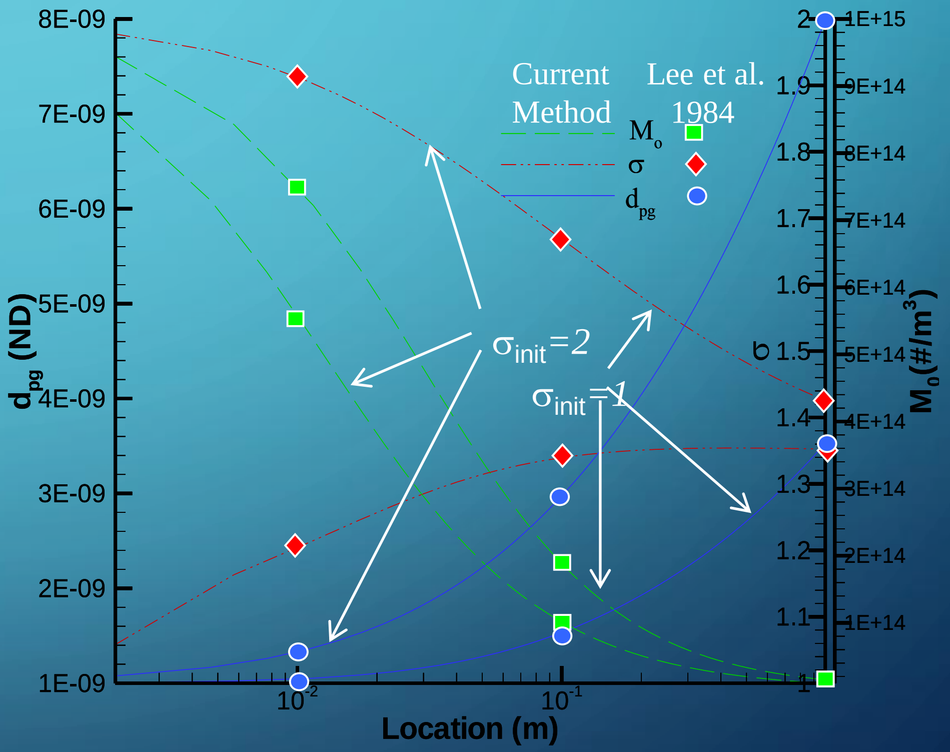
SOME VALIDATION AND EXAMPLES OF THE DISPERSED PHASE MOMENT MODEL

COAGULATION IN THE FREE-MOLECULAR AND CONTINUUM LIMITS

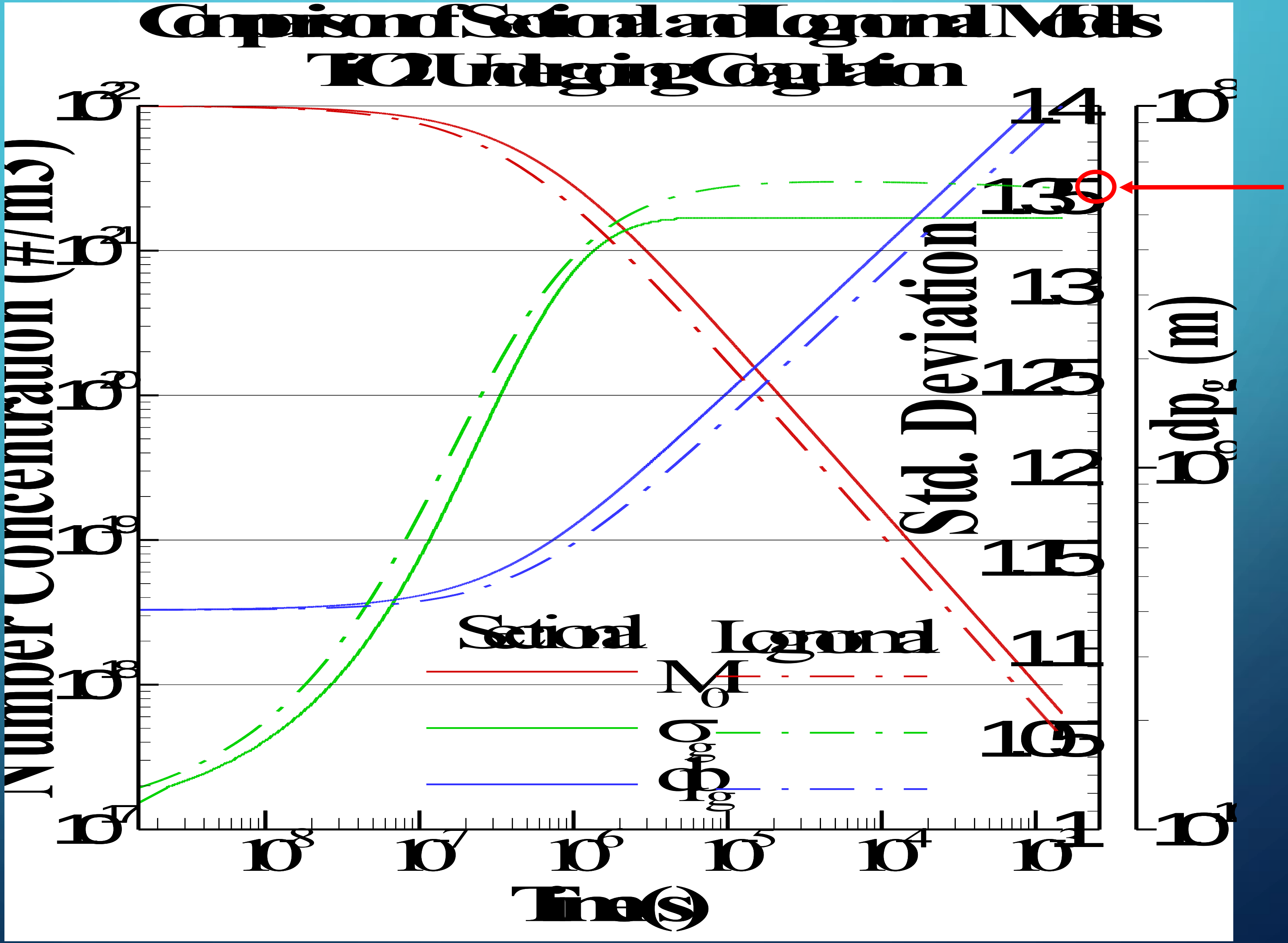
Continuum Limit
Comparison with Lee 1983



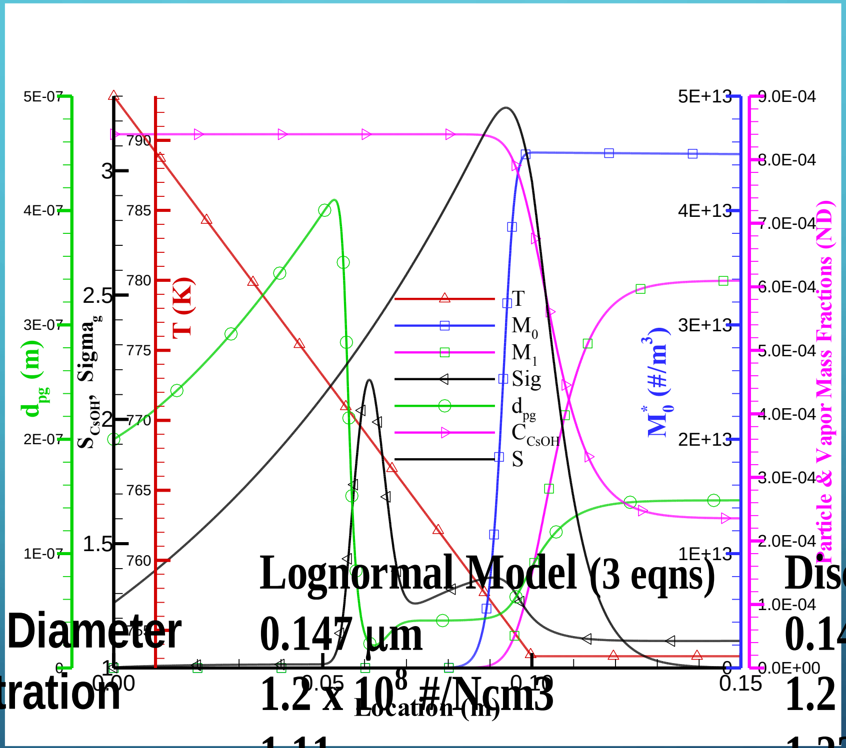
Free-Molecular Limit
Comparison with Lee 1984



COAGULATION WITH PARTICLE GROWTH FROM FREE-MOLECULAT TO CONTINUUM LIMITS

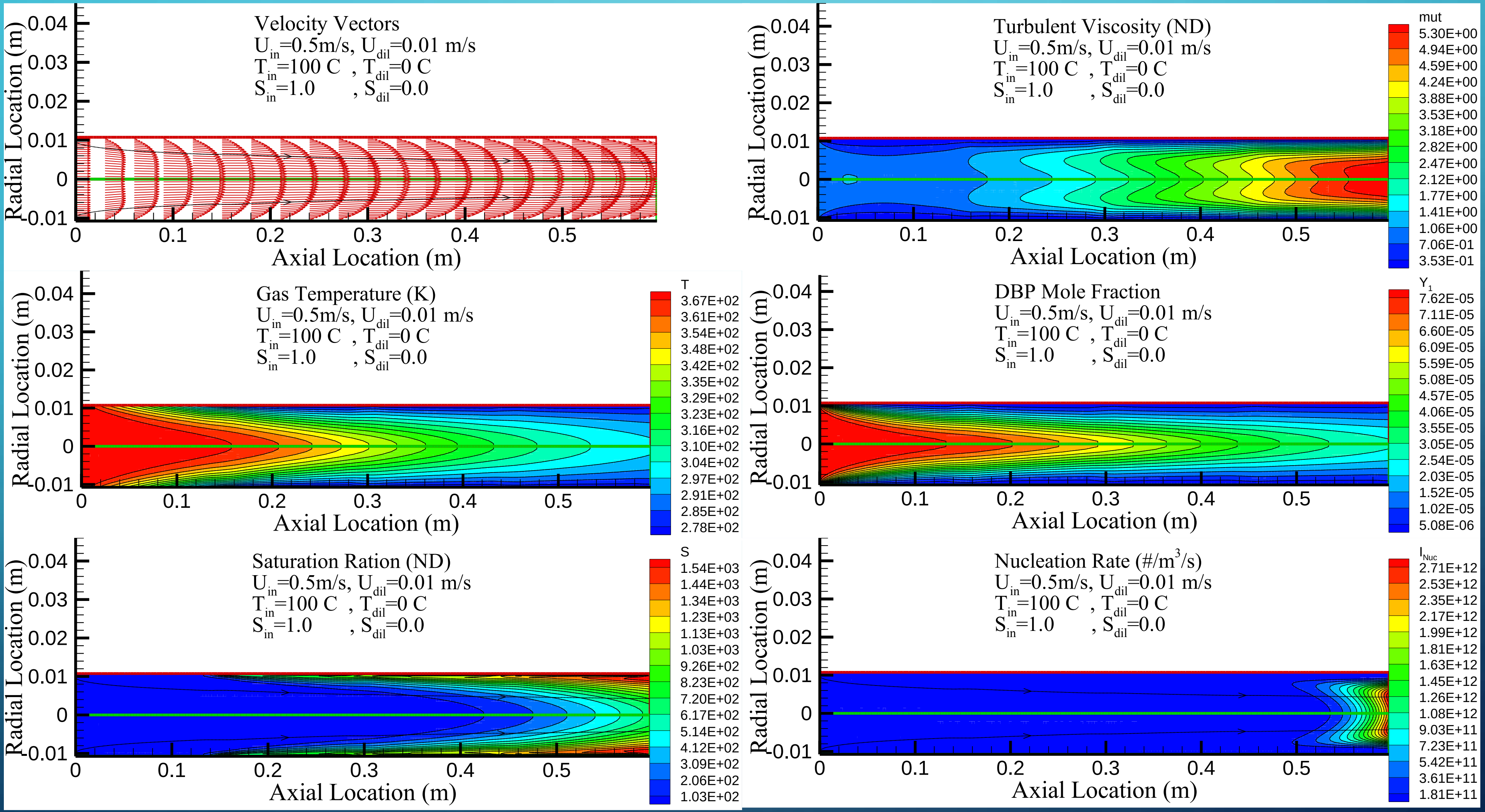


SIMULTANEOUS NUCLEATION, CONDENSATION DYNAMICS IN A NANOPARTICLE REACTOR

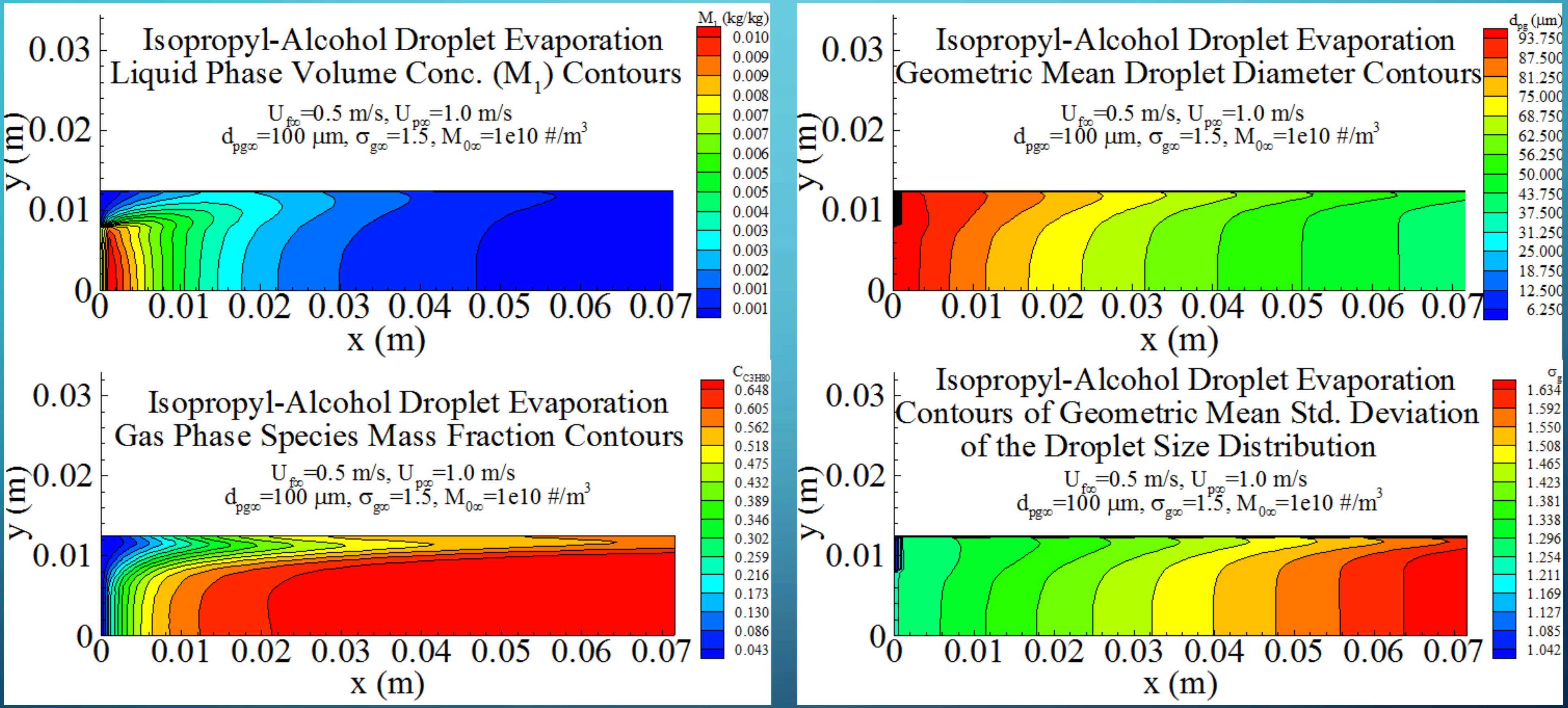


	Lognormal Model (3 eqns)	Discrete Sectional (300 eqns)
Geometric Mean Aerosol Diameter	0.147 µm	0.147 µm
Aerosol Number Concentration	1.2×10^8 #/Ncm3	1.2×10^8 #/Ncm3
Standard Deviation	1.11	1.22
Peak Saturation Ratio	3.25	3.26
Percent of Aerosol in Condensed Phase	71.9%	71.8%

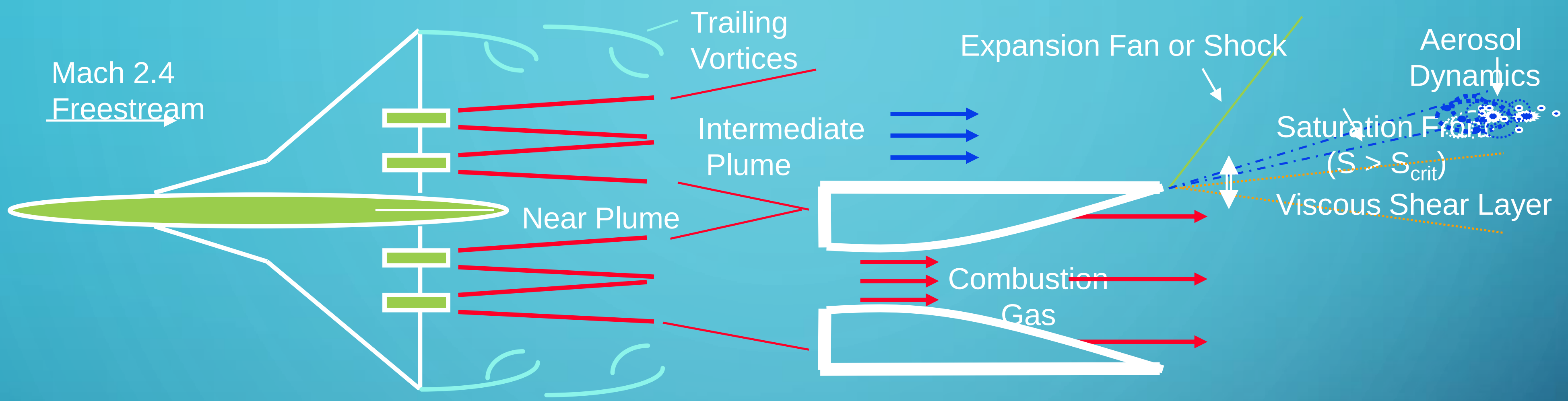
FLOW AND SPECIES CHARACTERISTICS IN NANOPARTICLE EMISSIONS SIMULATOR DEVICE

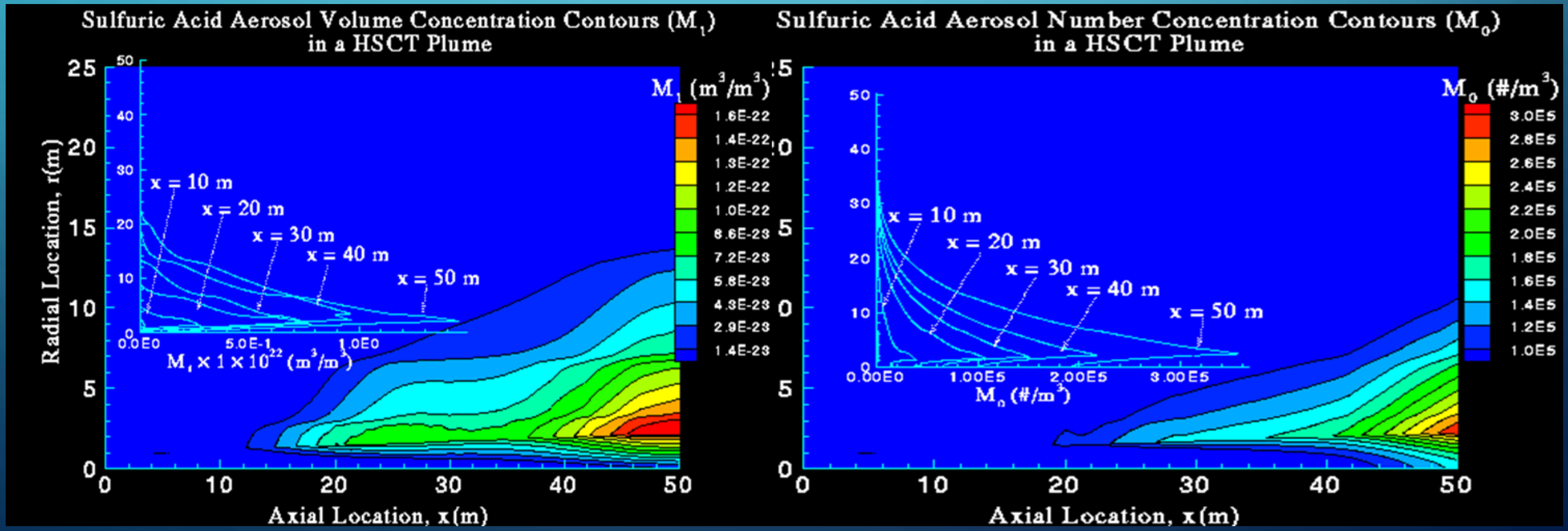


CONTROLLED ISOPROPYL-ALCOHOL DROPLET EVAPORATION IN A HEATED REACTOR FOR MICROPARTICLE PRODUCTION REACTOR

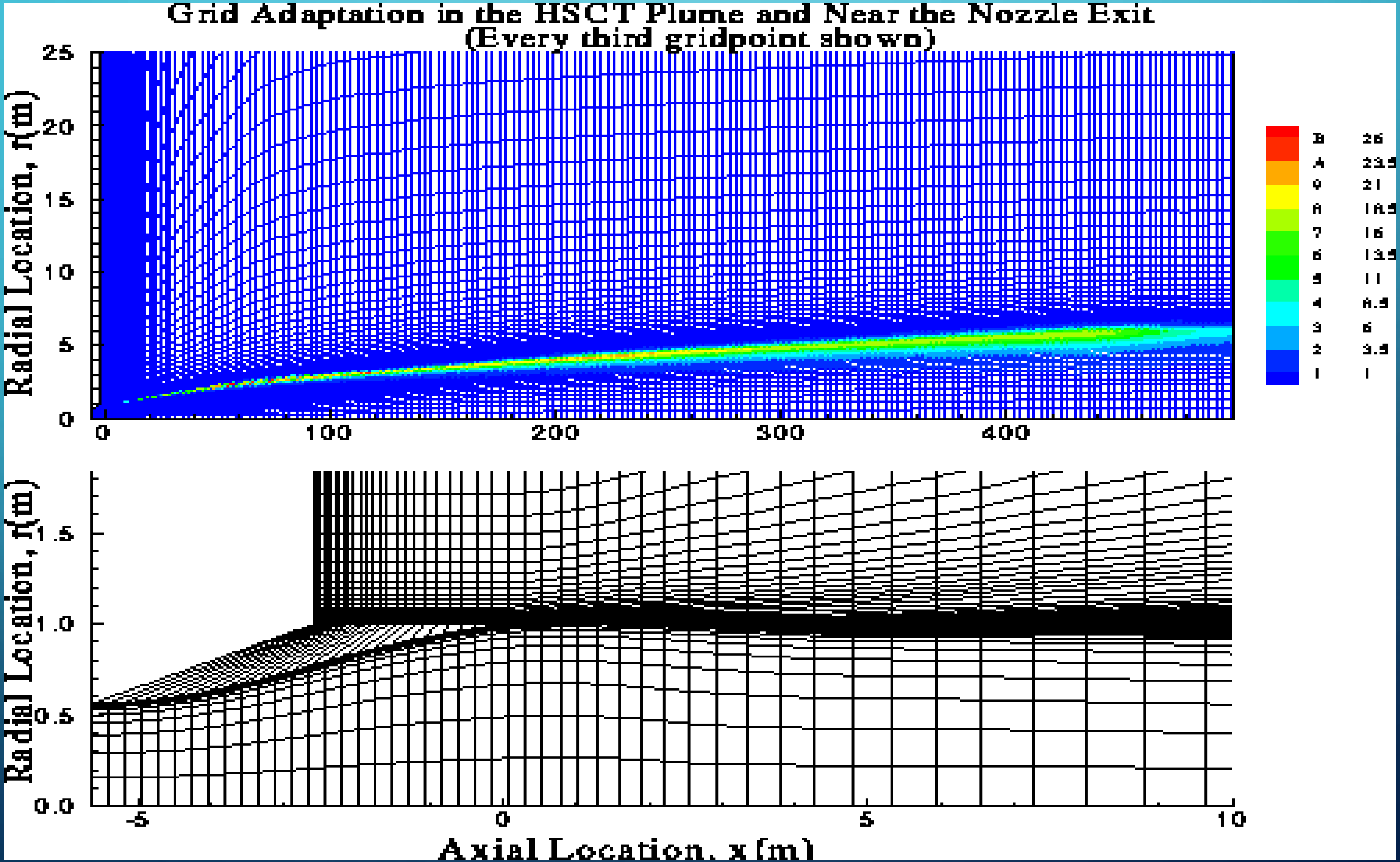


PARTICLE FORMATION IN A SUPERSONIC AIRCRAFT PLUME



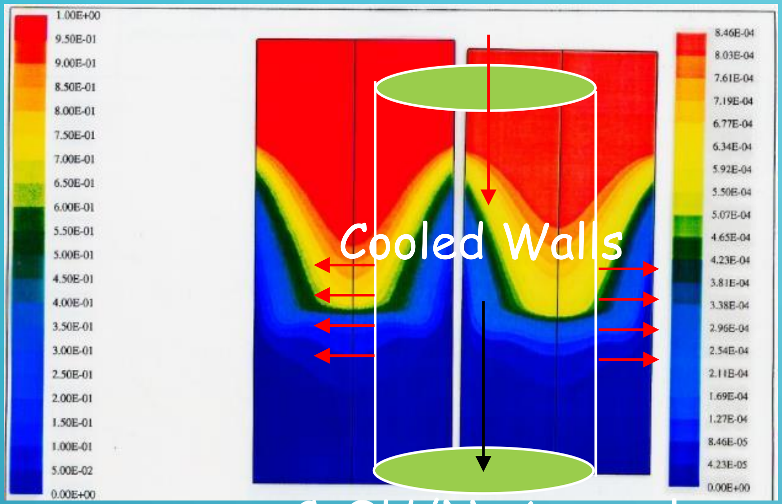


GRID ADAPTATION IN A SUPERSONIC AIRCRAFT PLUME

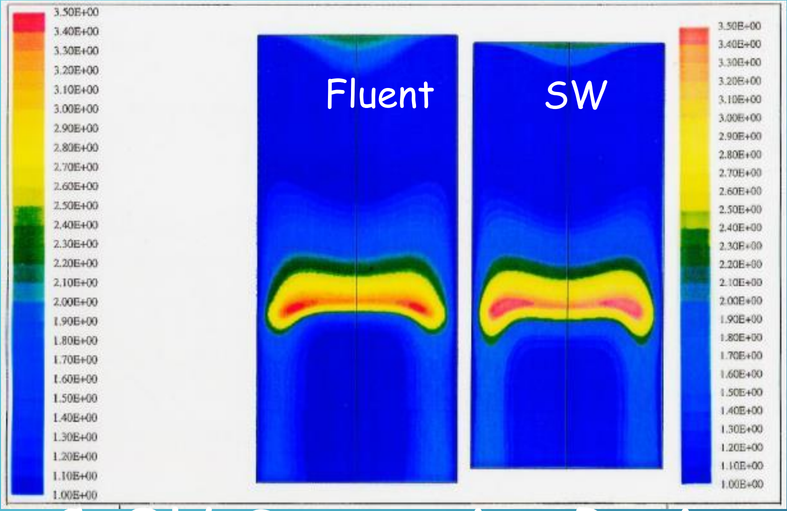


NANOPARTICLE FORMATION IN NUCLEAR REACTOR"TBD" TOKEN VS. FLUENT WITH ADD-ON PARTICLE MODEL

CsOH Saturated N_2

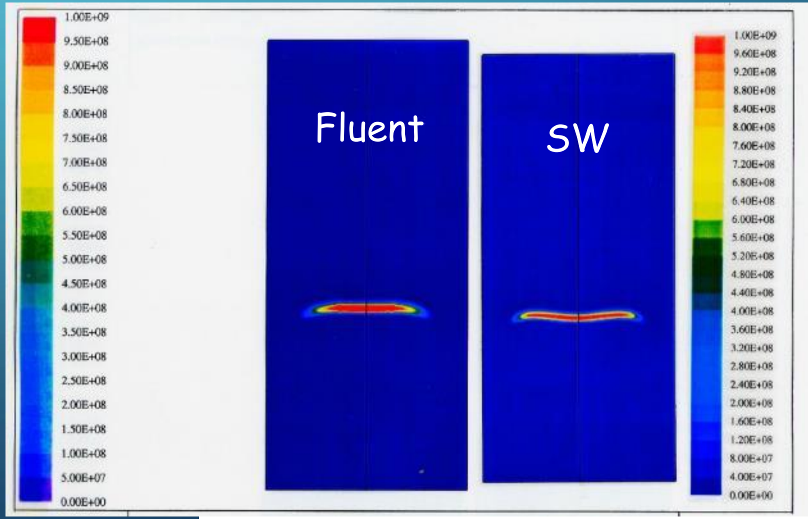


CsOH/N_2 Aerosol



CsOH Saturation Ratio

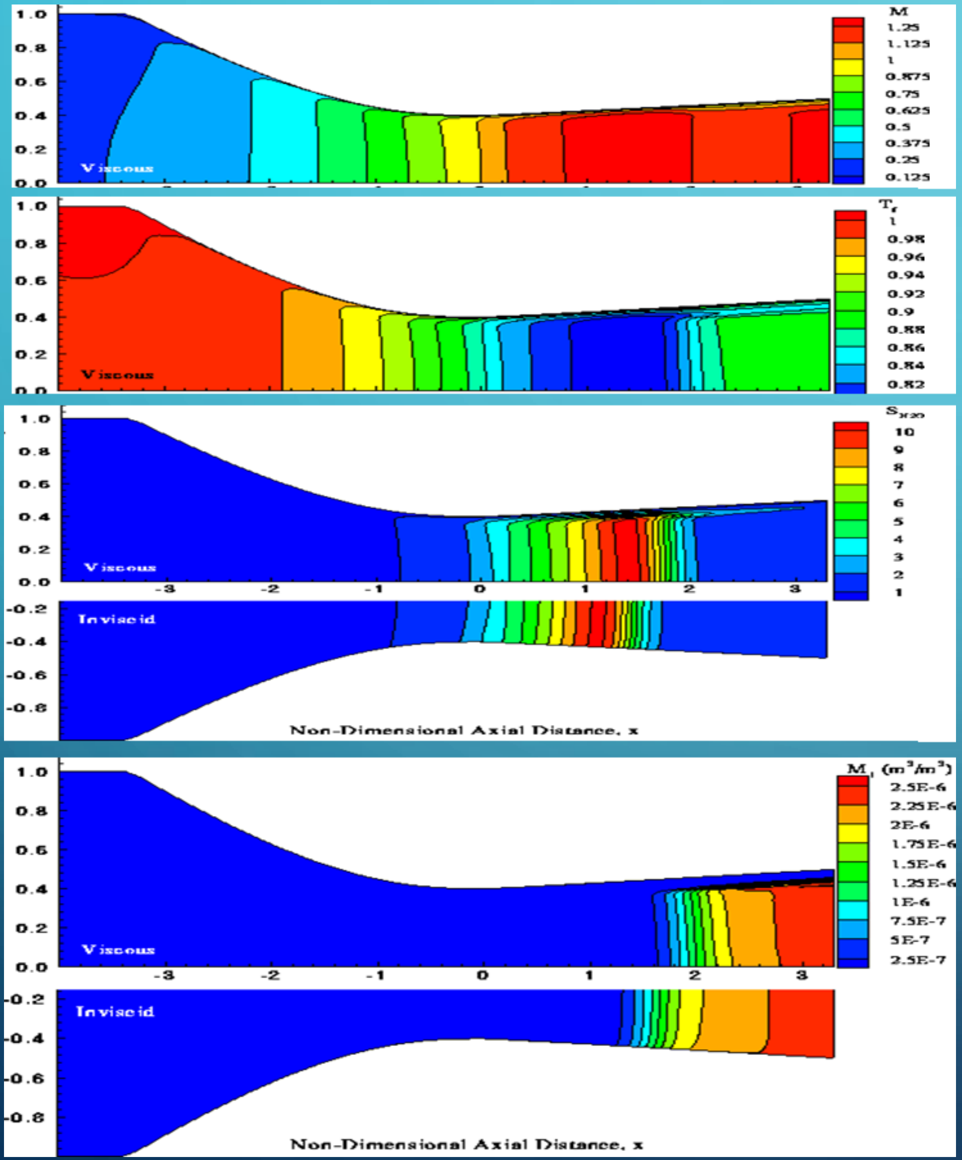
Fluent SW

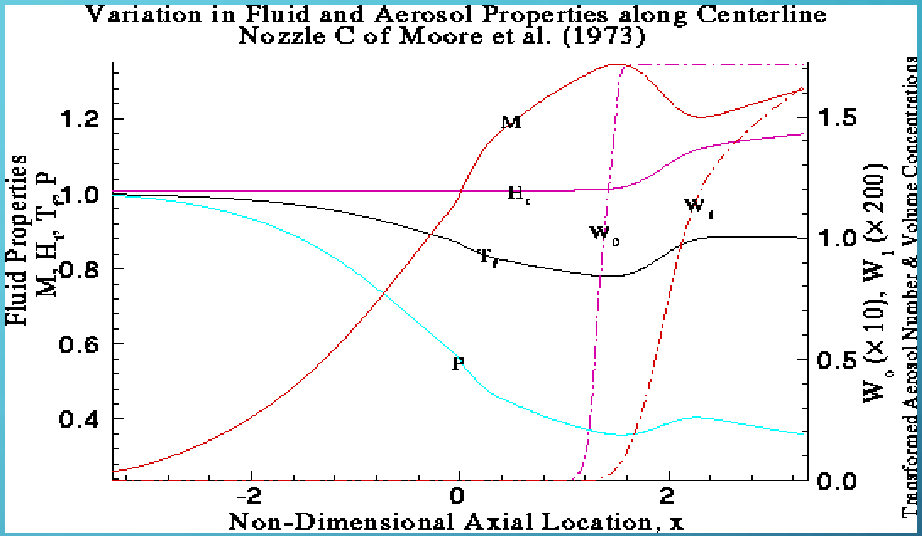


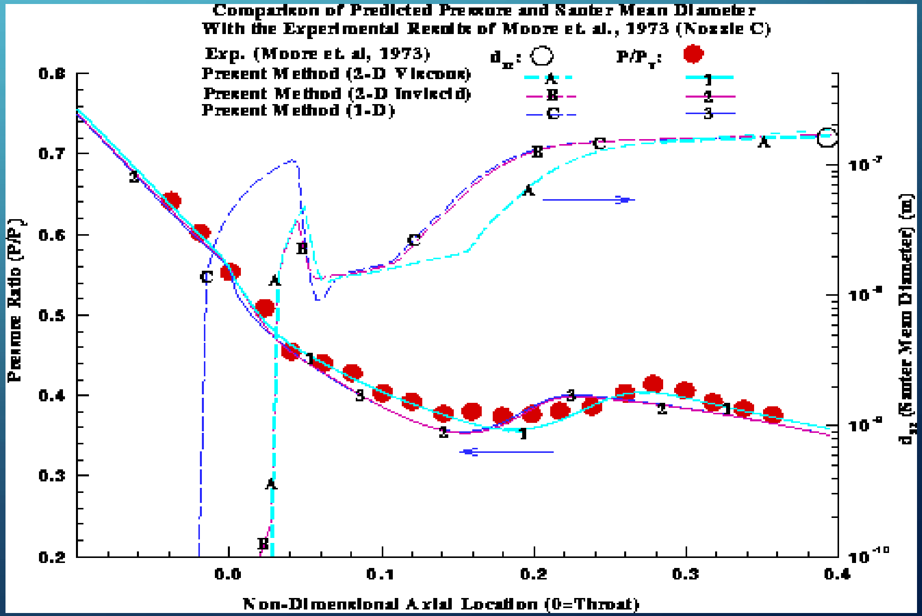
CsOH Vapor Concentration

CsO

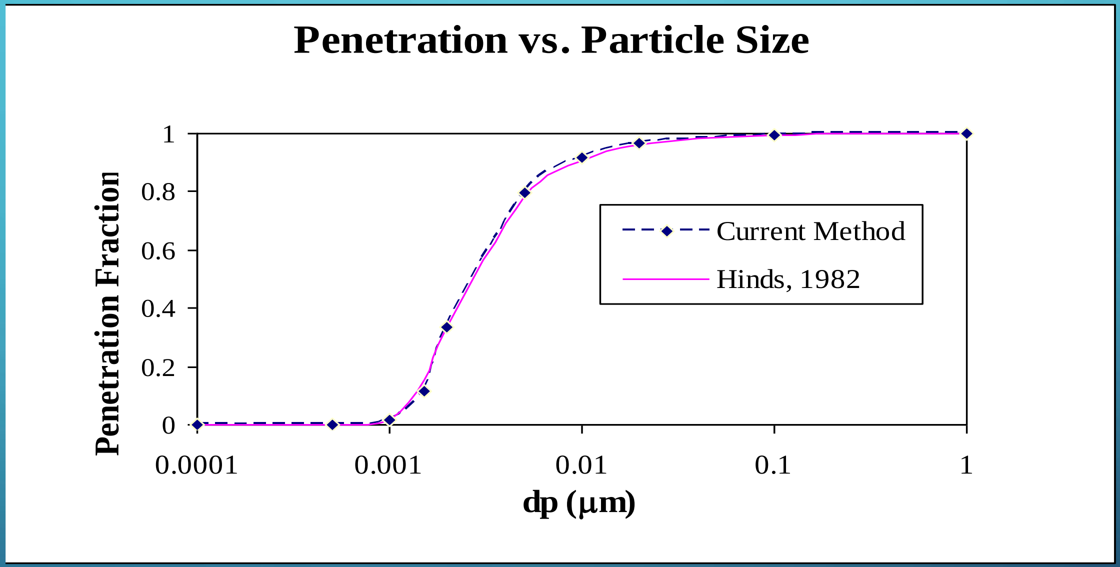
CONDENSATION SHOCK IN A WET STEAM NOZZLE



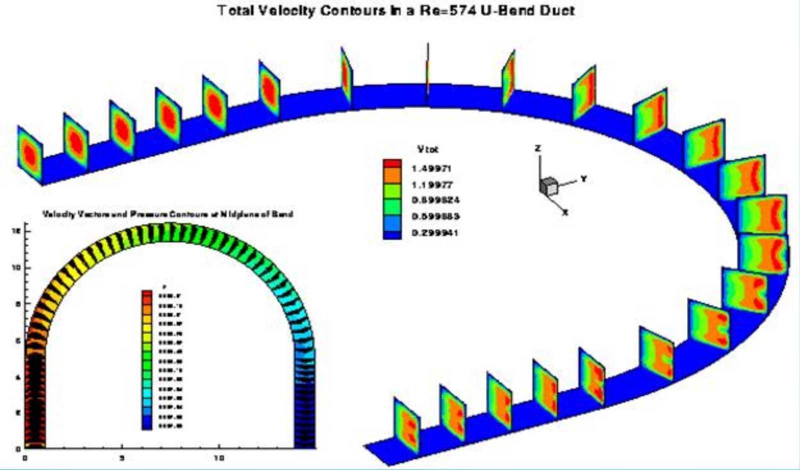


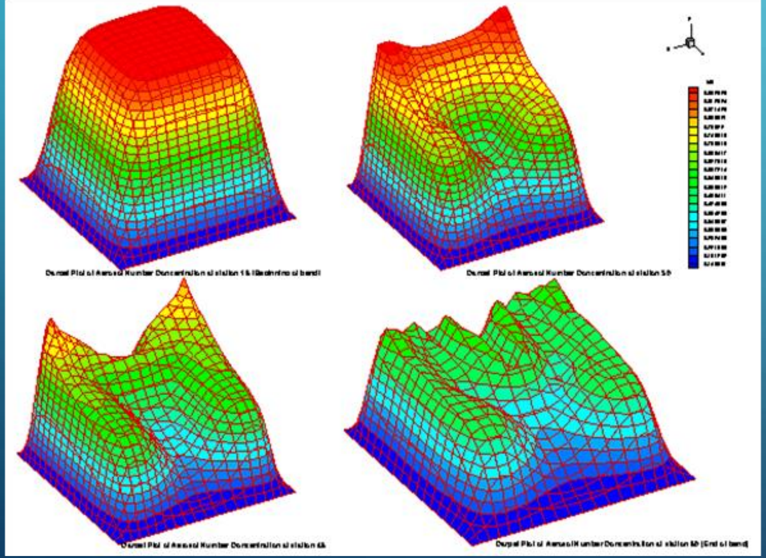


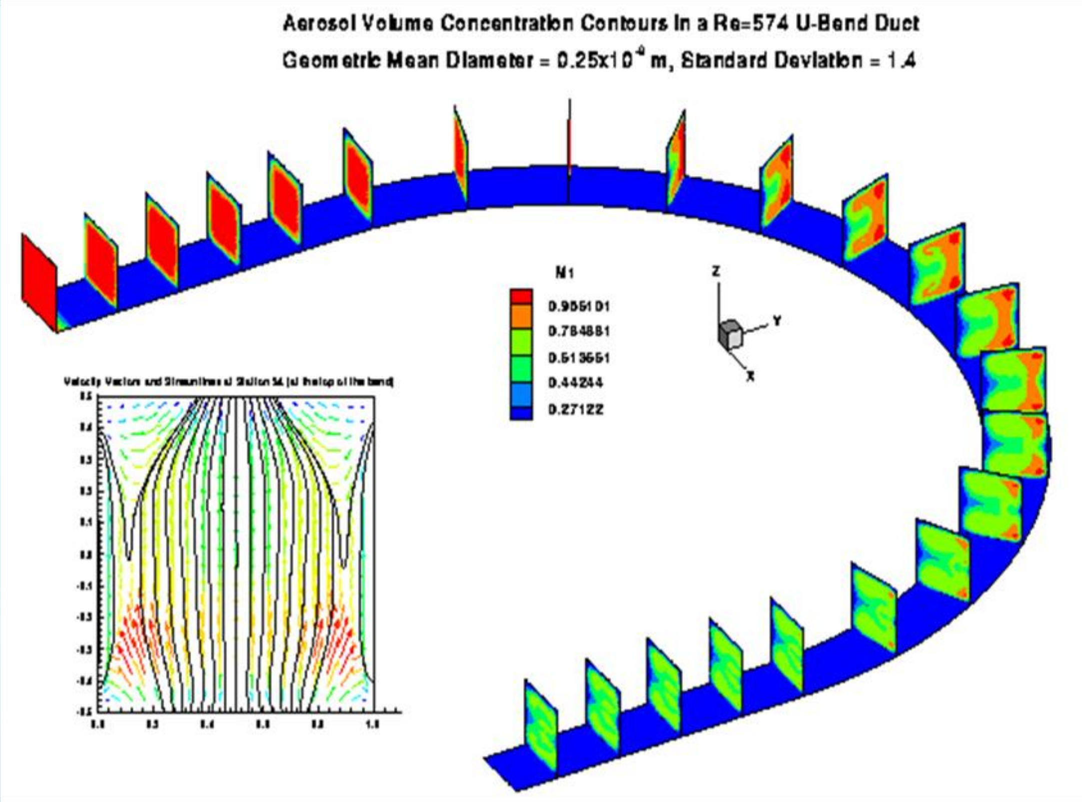
PARTICLE DEPOSITION IN A DIFFUSION BATTERY



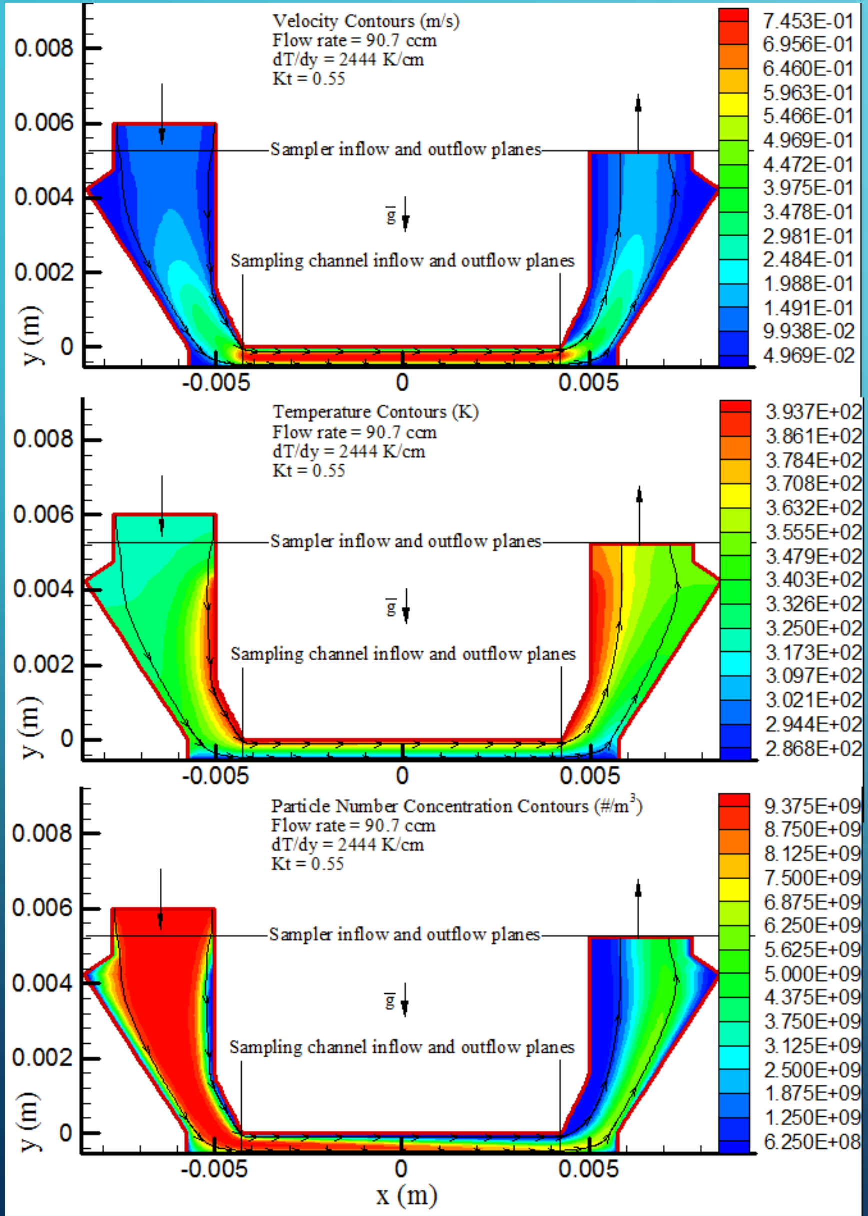
NANOPARTICLE DEPOSITION IN A BEND





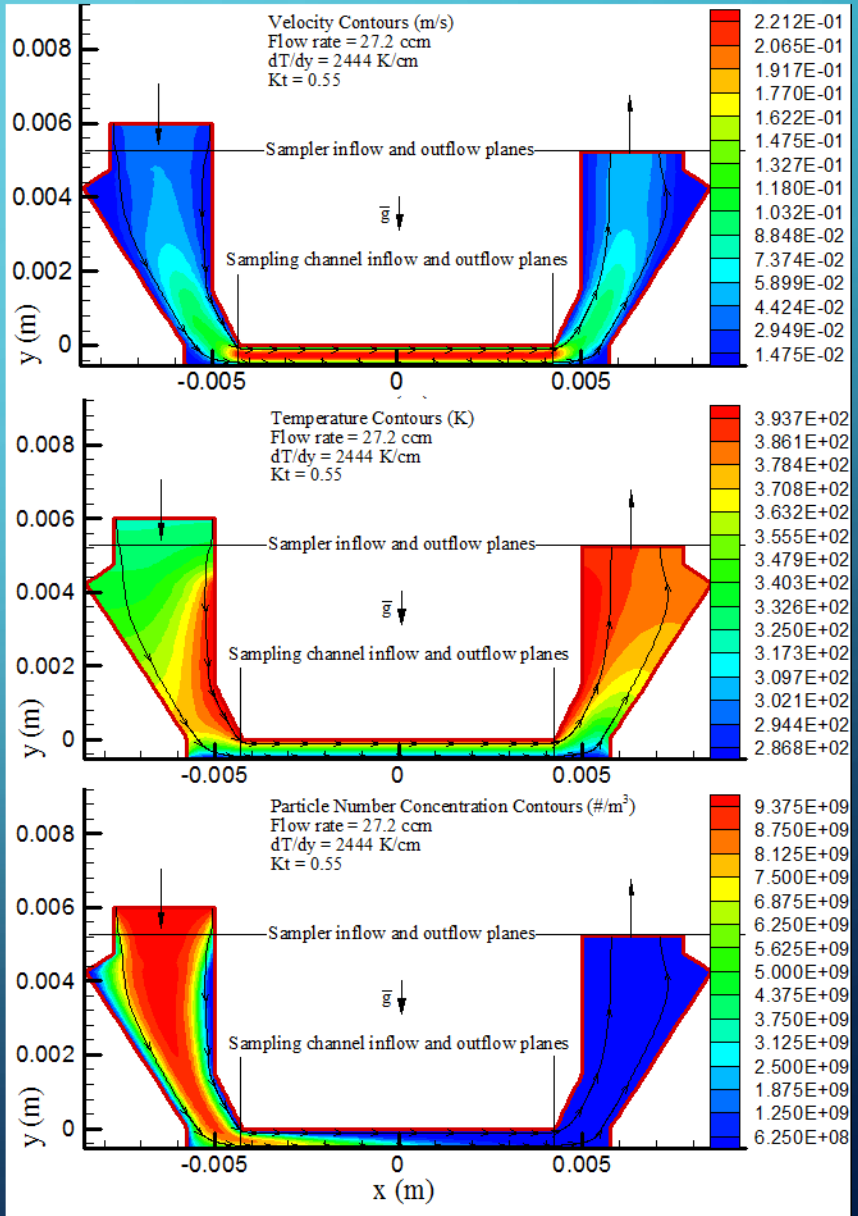


THERMOPHORETIC AND DIFFUSIONAL DEPOSITION NANOPARTICLES IN A TEMPERATURE GRADIENT

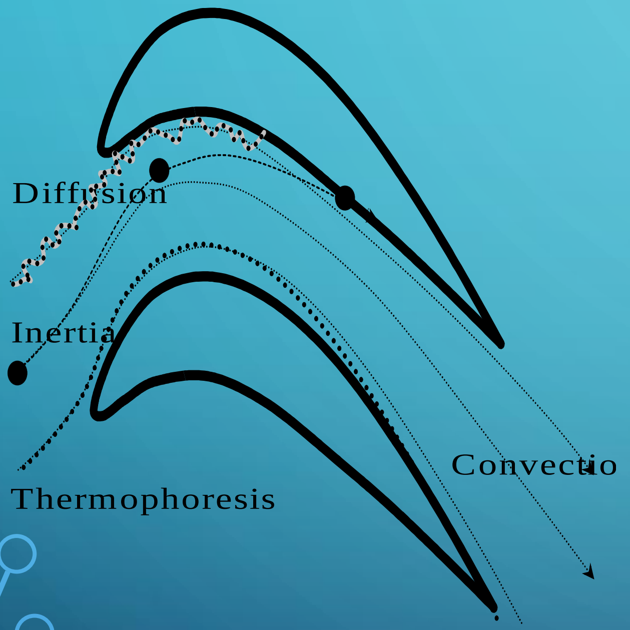


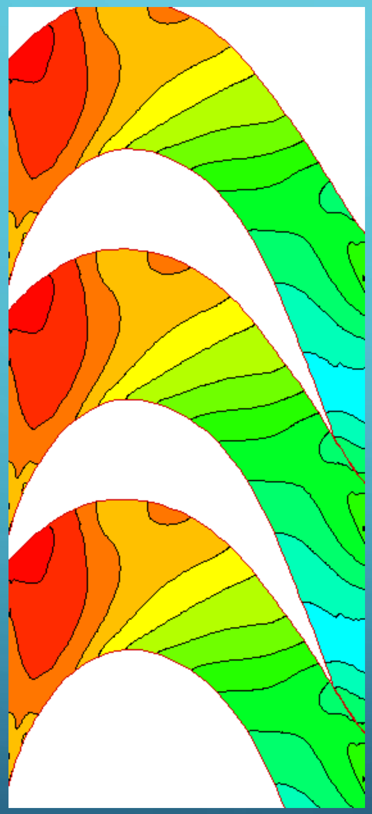
High Flow Rate (90.7 ccm)

Low Flow Rate (27.2 ccm)

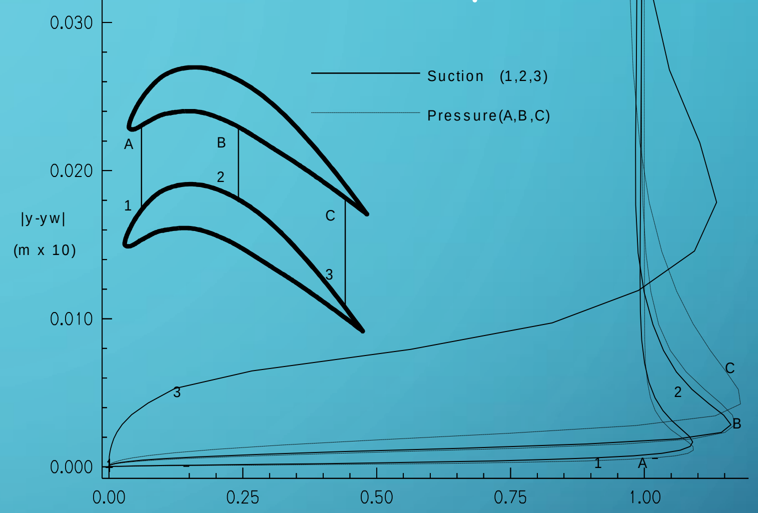


Soot Particle Deposition in a Gas Turbine

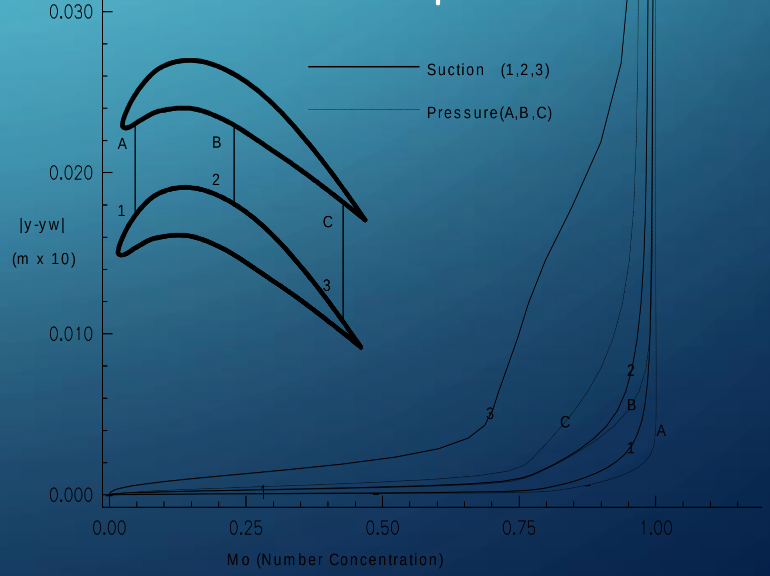




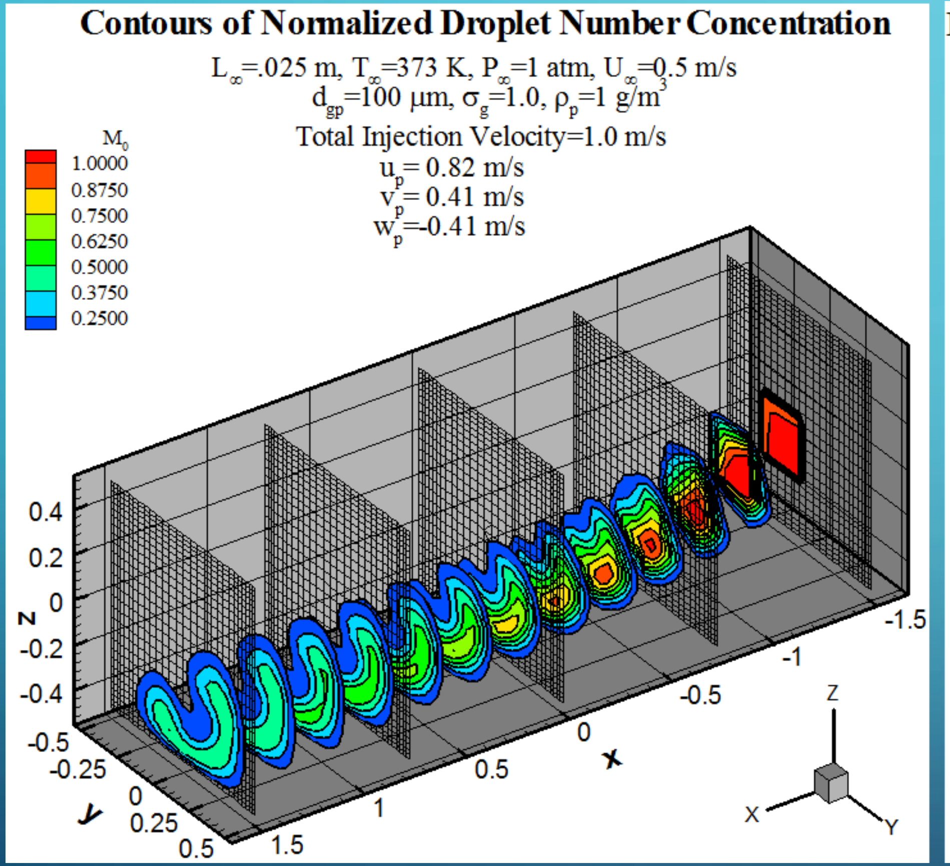
Without Thermophoresis

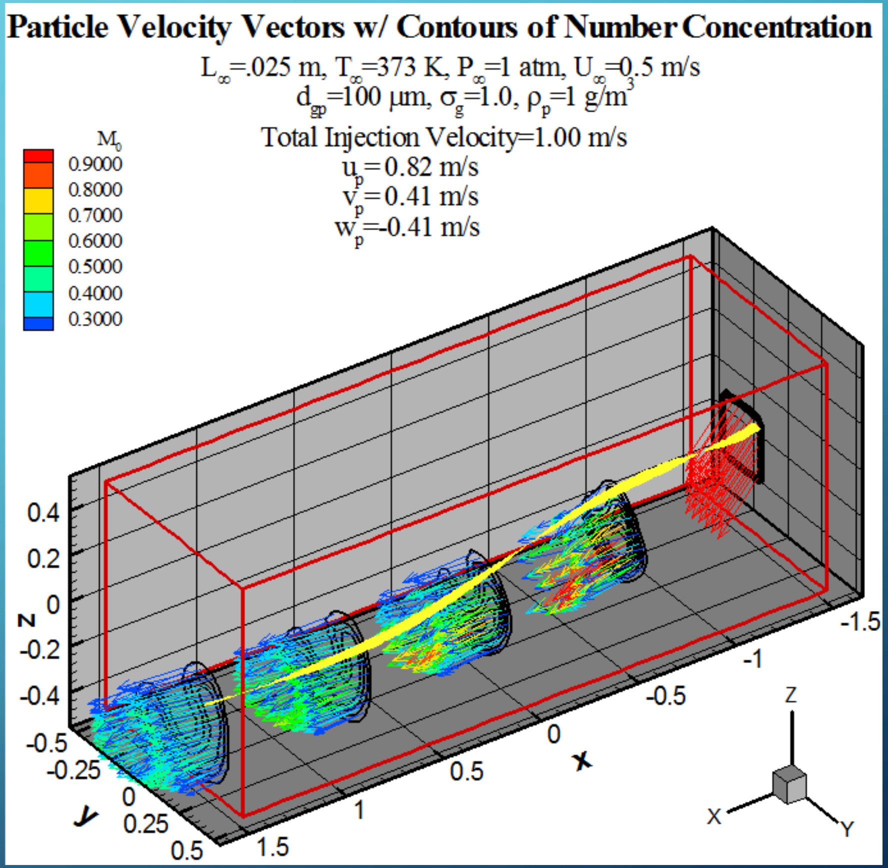


With Thermophoresis

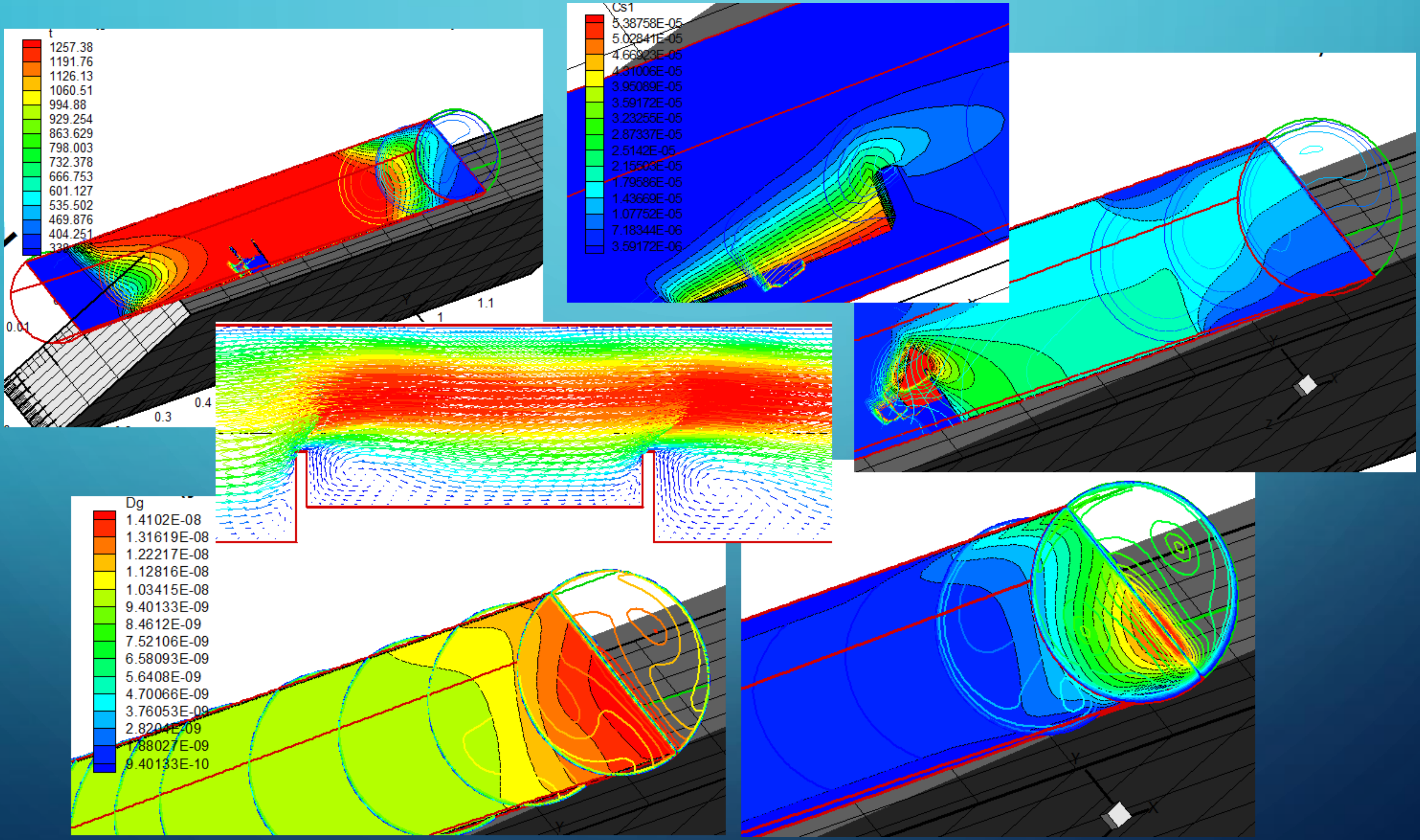


DROPLET INJECTION WITH HIGH INERTIA IN A SPRAY COMBUSTOR

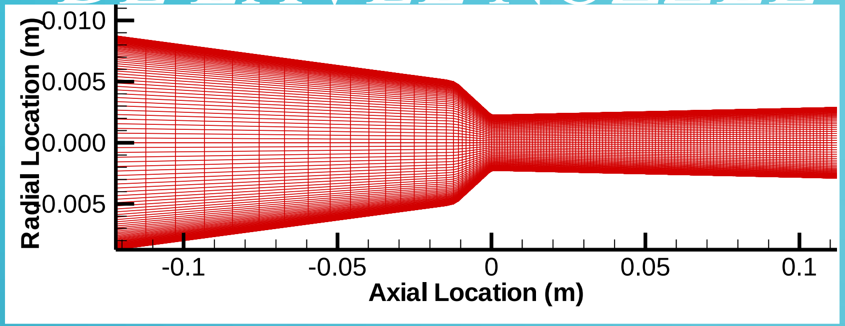


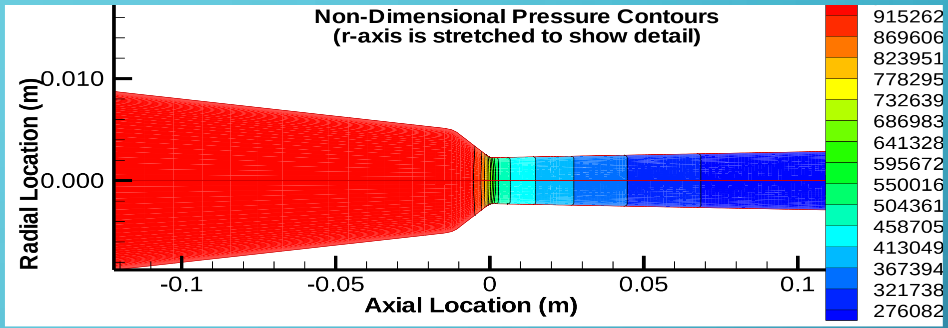


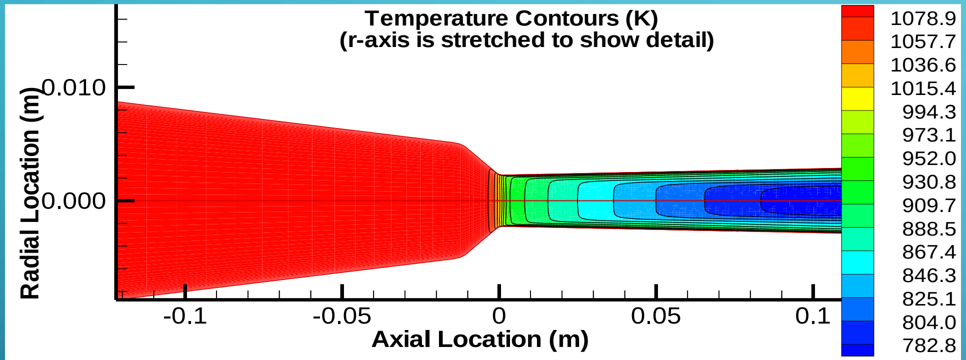
METAL NANOCATALYST PRODUCTION BY CONDENSATION NUCLEATION

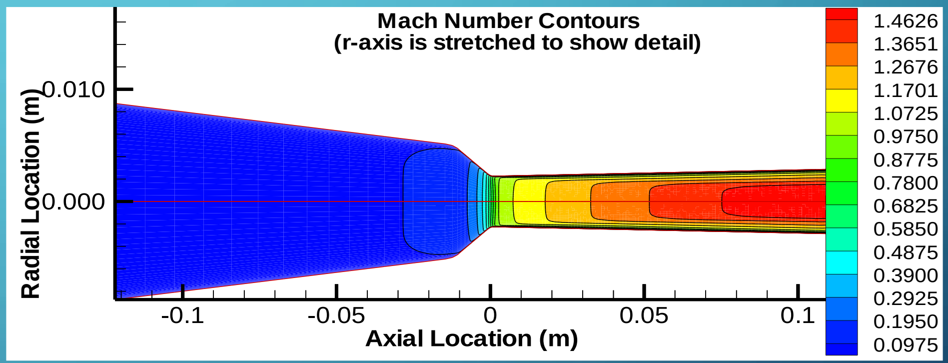


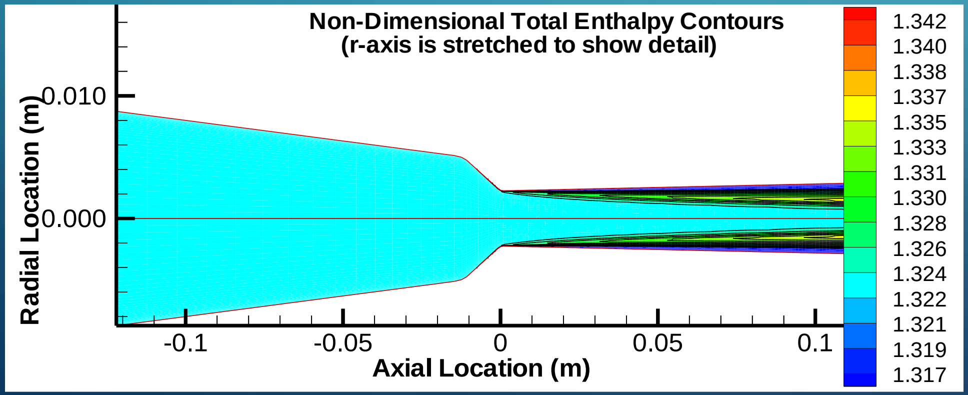
METAL NANOPARTICLE NUCLEATION IN A TRANSONIC DE LAVEL NOZZLE

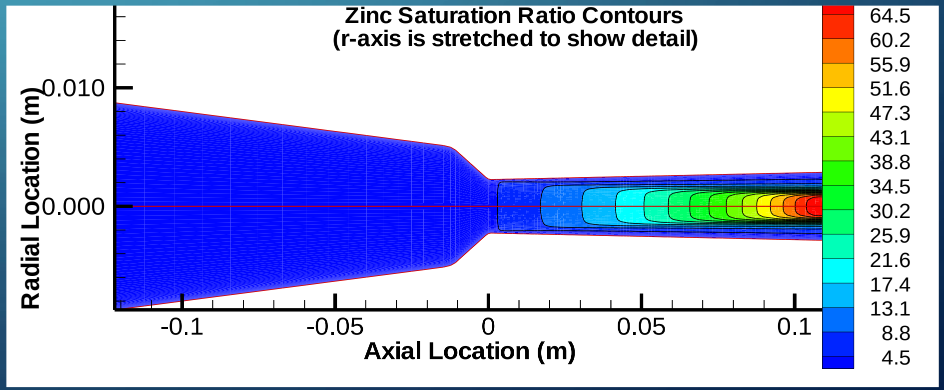






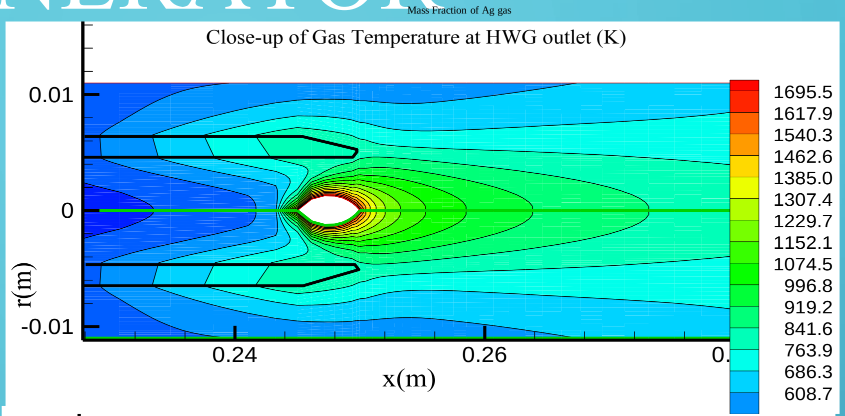




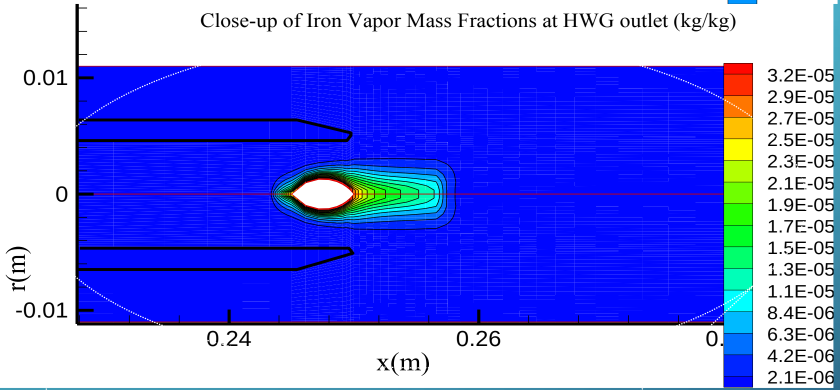


NUCLEATION OF NANOPARTICLES FROM A HOT WIRE GENERATOR

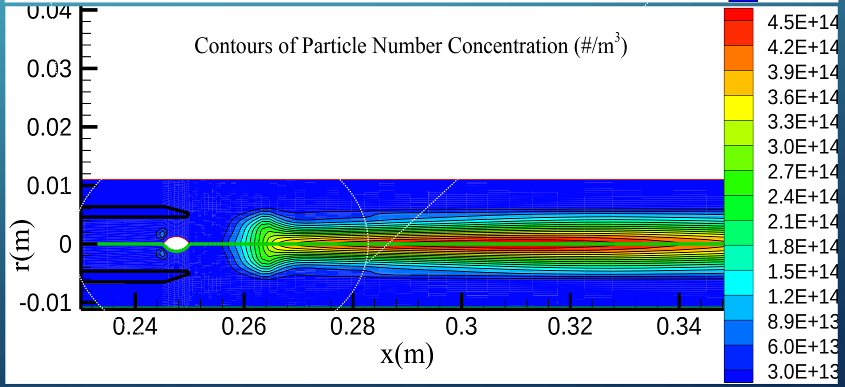
Gas Temperature



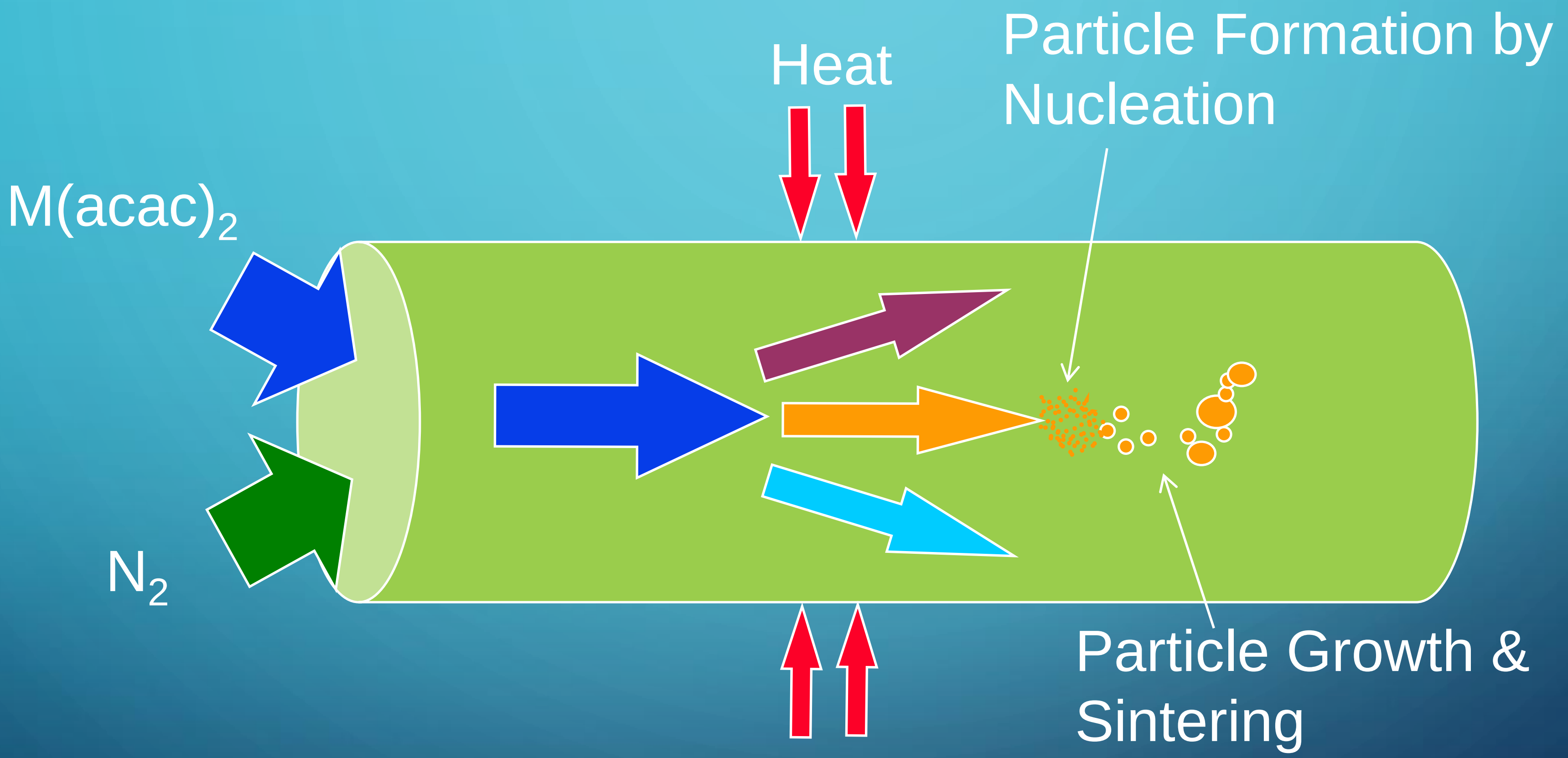
Iron Vapor Concentration



Iron Particle Number Concentration



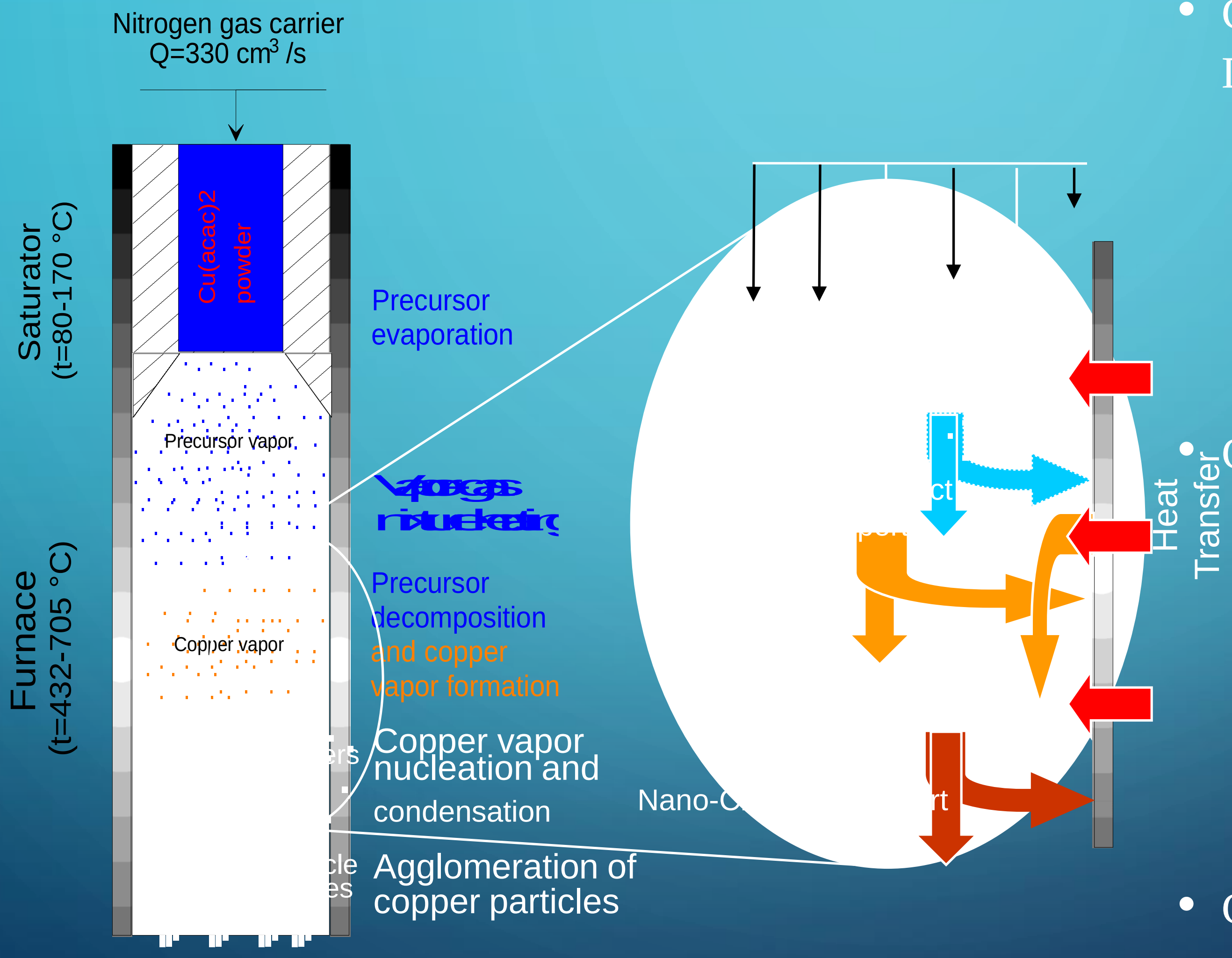
METAL NANO-CATALYST PARTICLE PRODUCTION BY THERMAL DECOMPOSITION OF METAL(ACAC)$_2$



$Cu(acac)_{2(vap)}$ --> $Cu_{(vap)}$

+ ethylene(CO) + CO_2 + acetone + H_2O + methylethylketone

MECHANISMS IN M(ACAC)$_2$ NANO-CATALYST REACTOR



- Cu(acac)$_2$ Precursor Decomposition
  - Homogeneous (gas phase)

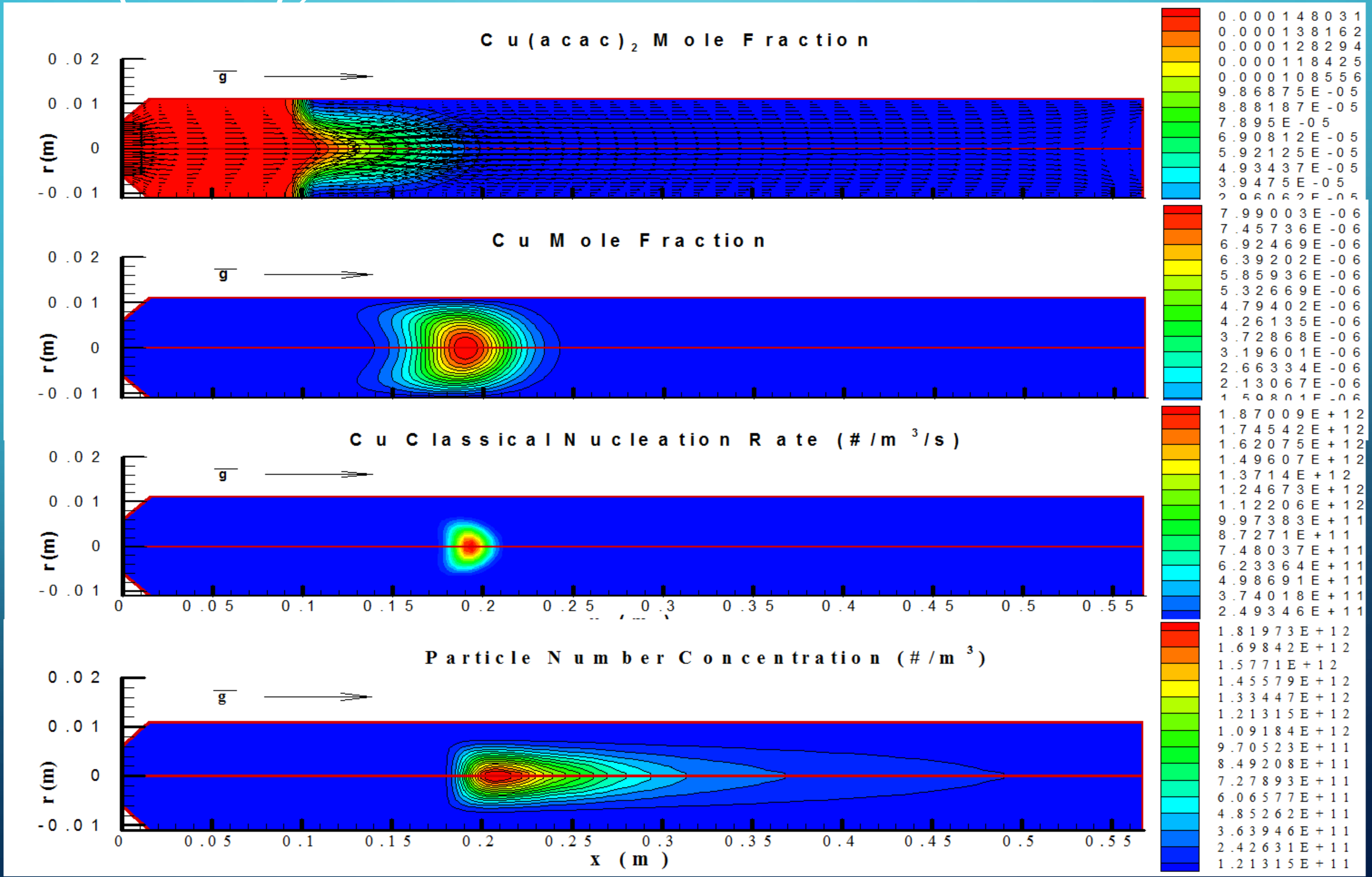
    vs. .
  - Heterogeneous (reactor walls & particle surfaces)
- Copper Vapor Depletion
  - Homogeneous Nucleation

    vs. .
  - Wall Condensation

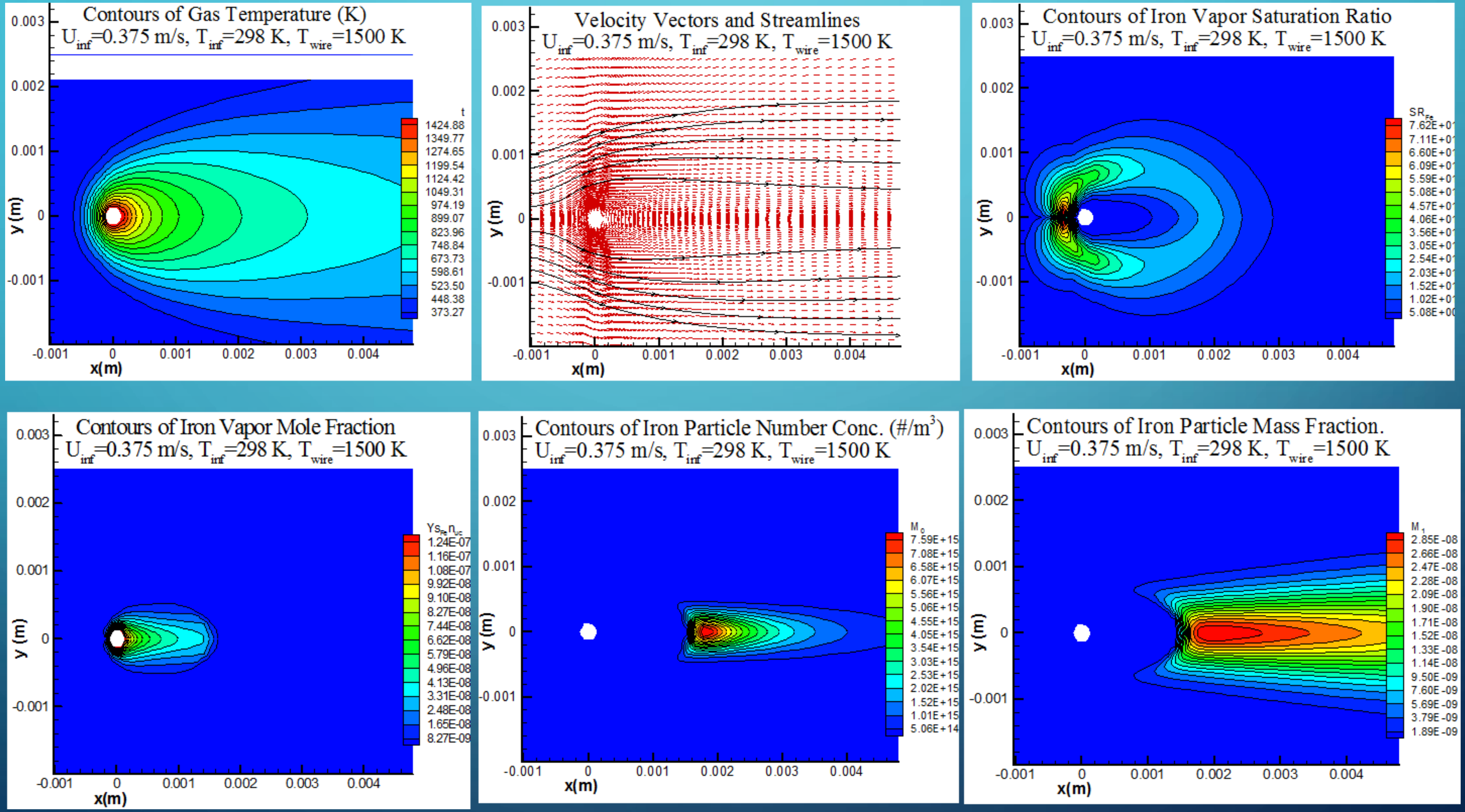
    vs. .
  - Particle Surface Condensation
- Copper Particle Morphology
  - Coagulation

    vs. .

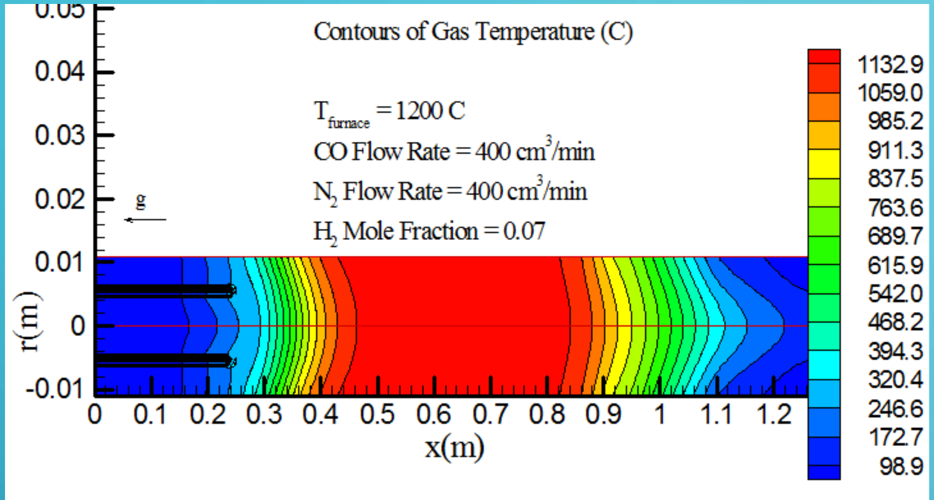
METAL NANOPARTICLE PRODUCTION VIA $CU(ACAC)_2$ THERMAL DECOMPOSITION

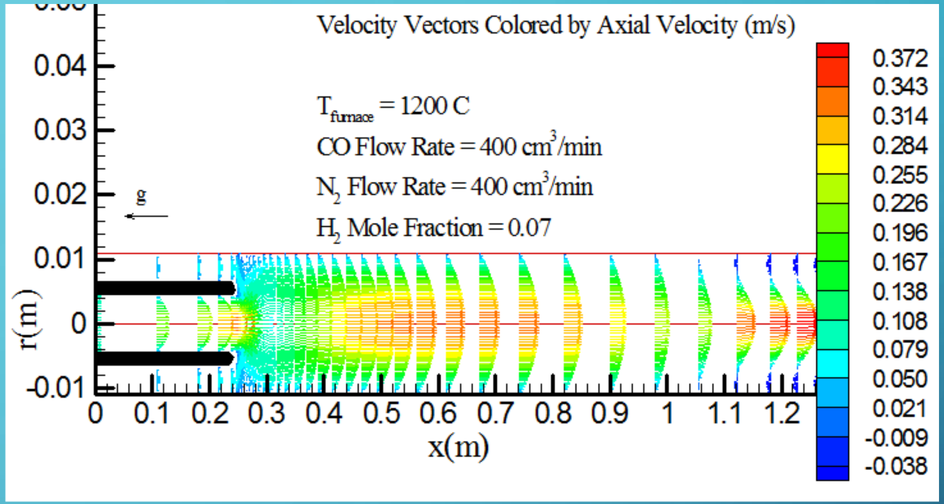


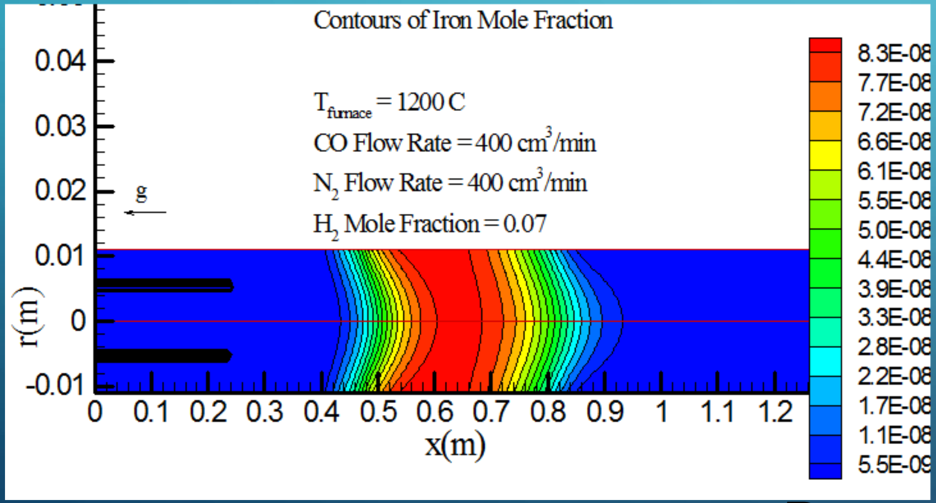
NUCLEATION OF METAL NANOPARTICLE CATALYSTS FROM A HOT WIRE

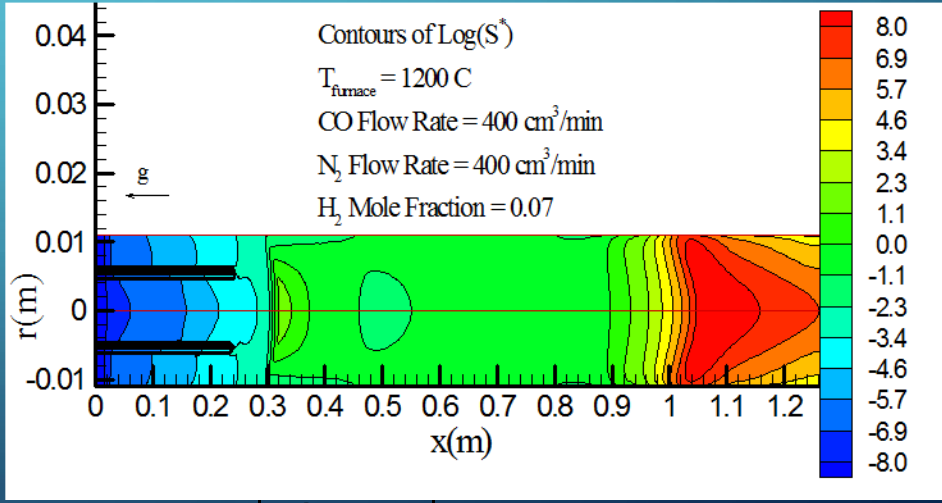


GAS CONDITIONS IN A NANOMATERIAL SYNTHESIS REACTOR





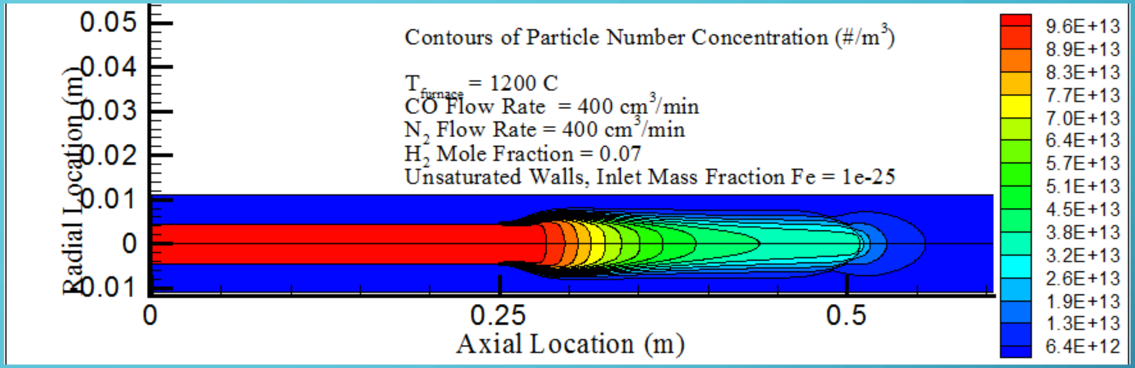




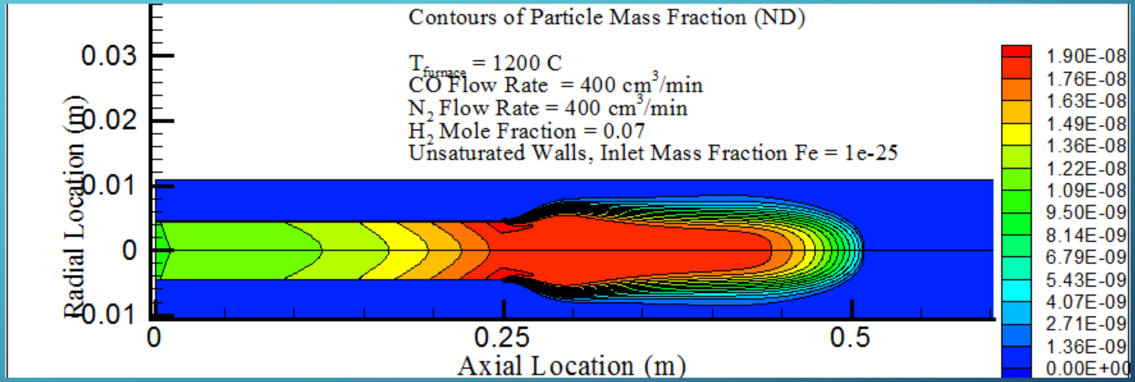
$$S^* = \frac{P_{Fe}}{P_{eq}^*} \qquad P_{eq}^* = P_{eq}^o \exp\left[\frac{2\sigma V}{r k_B T}\right]$$

CATALYST NANOPARTICLE DYNAMICS

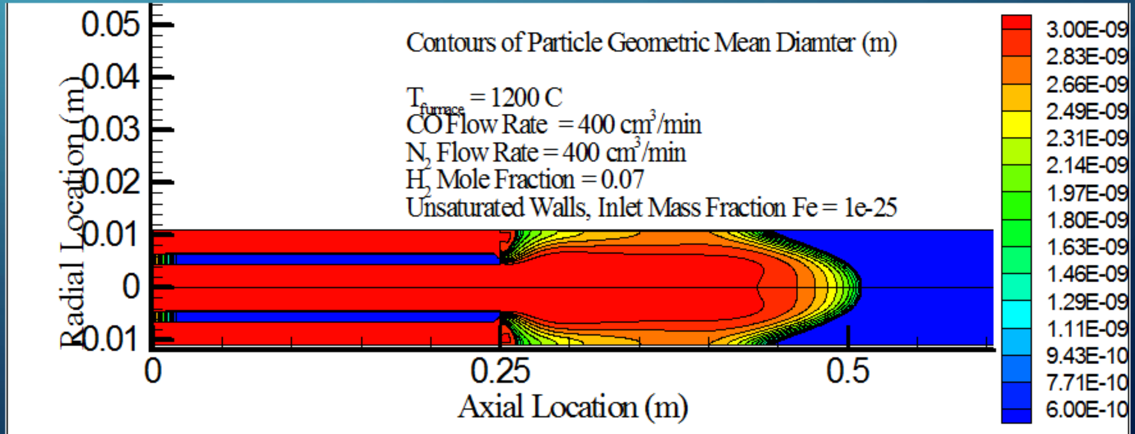
Particle Number Concentration



Particle Mass Fraction

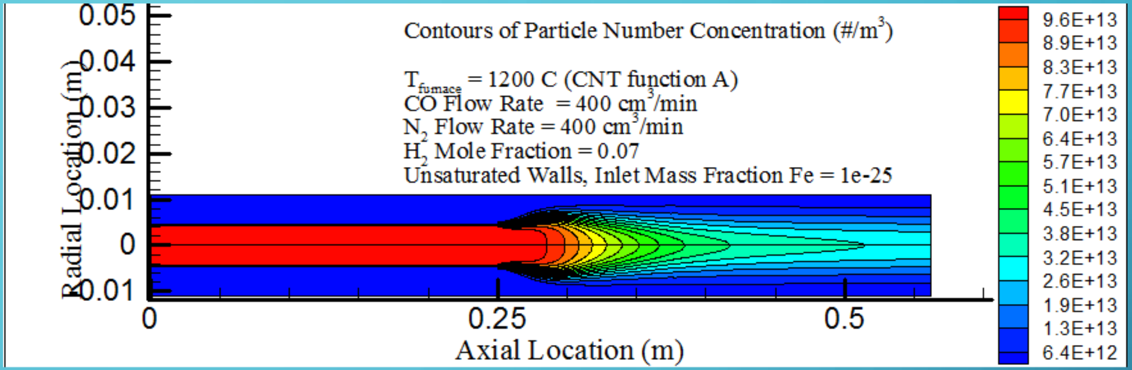


Effective Mean Particle Diameter

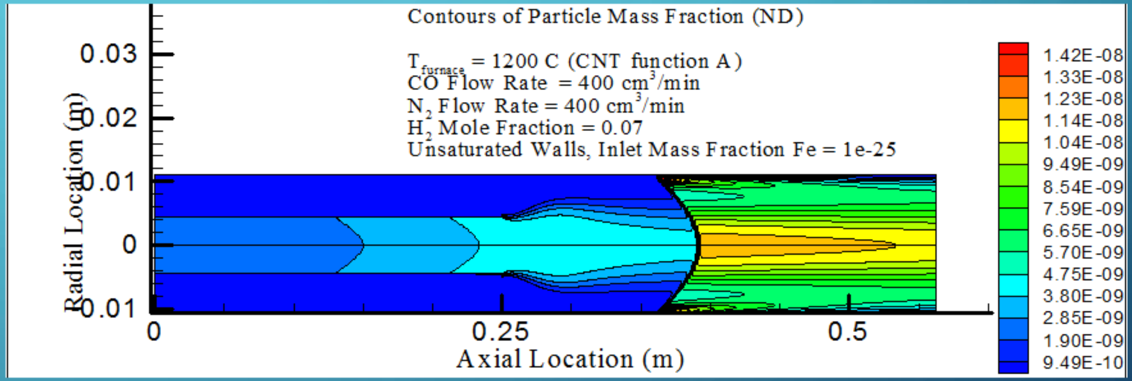


CATALYTIC FORMATION AND GROWTH OF NANOMATERIALS

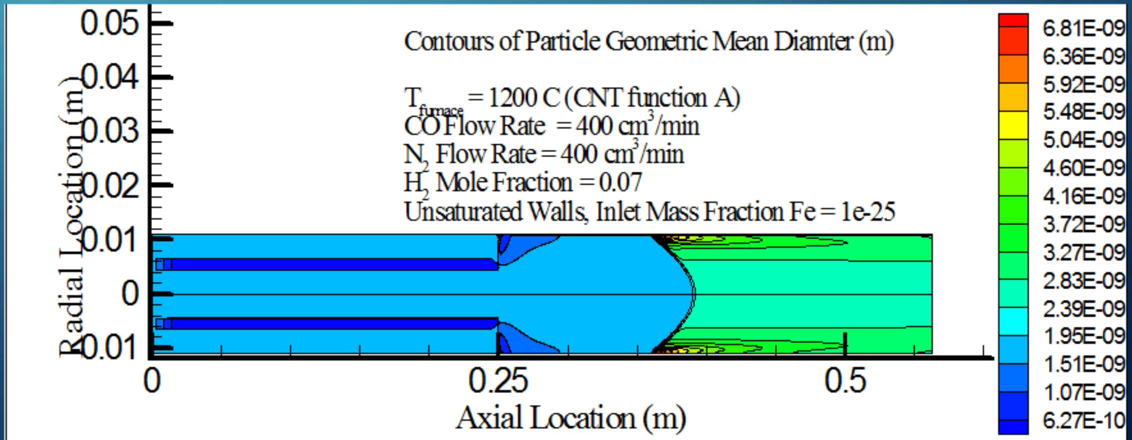
Particle Number Concentration



Particle Mass Fraction

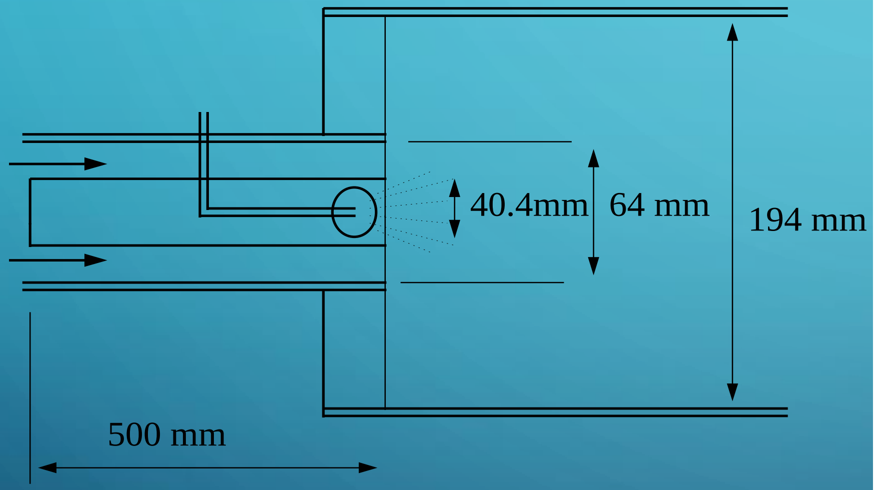


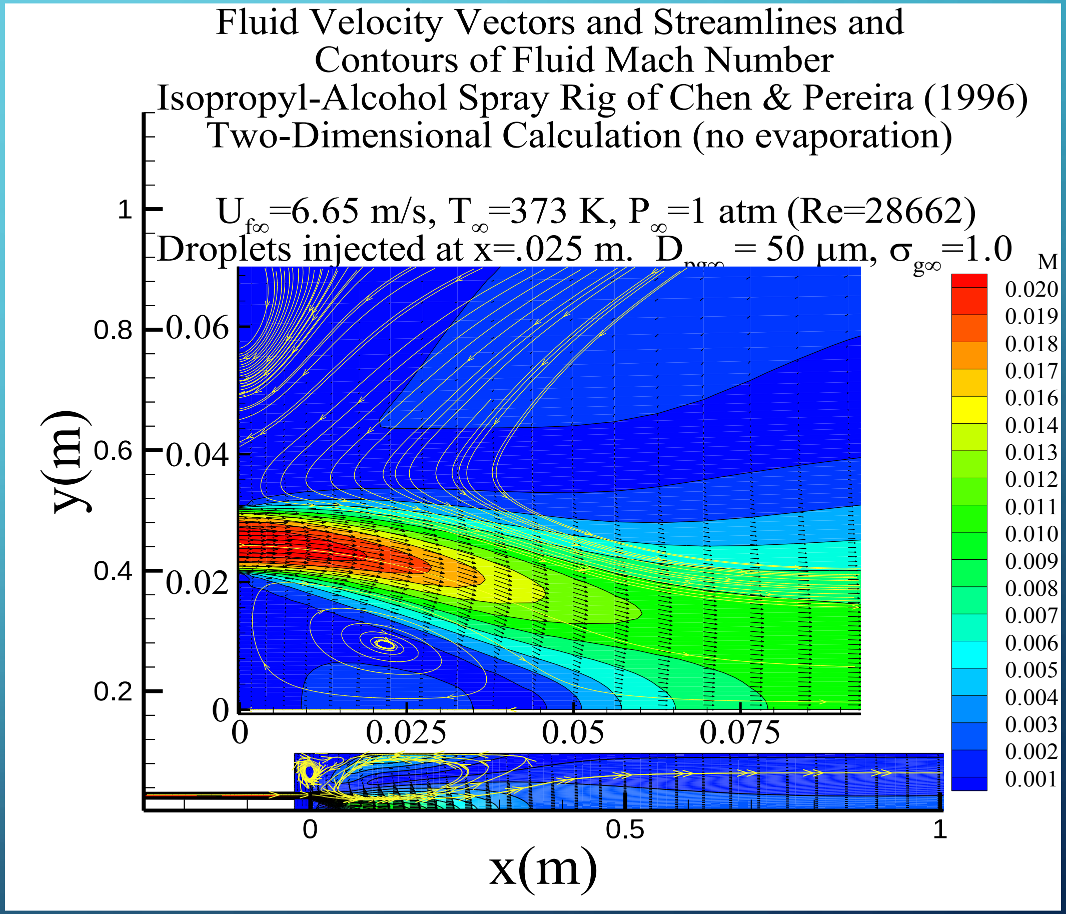
Effective Mean Particle Diameter



FLOW IN A SPRAY COMBUSTION CHAMBER

Schematic of Spray Nozzle Configuration of Chen and Pereira (1996)





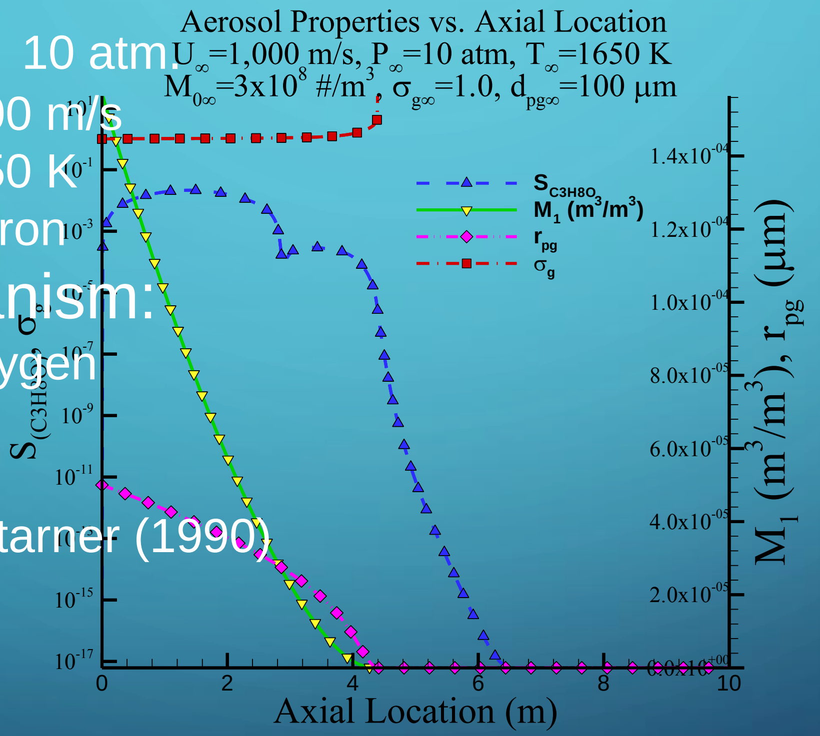
DROPLET COMBUSTION IN A SHOCK WAVE

Conditions:

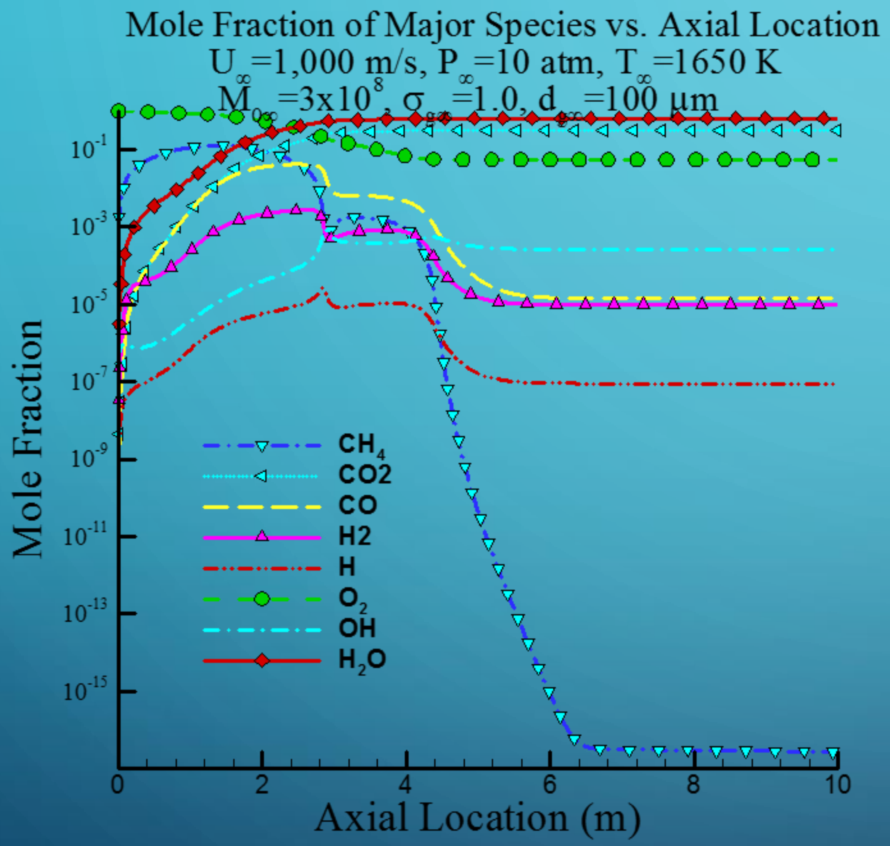
P	10 atm
u	1000 m/s
T	1650 K
dp_g	100 micron

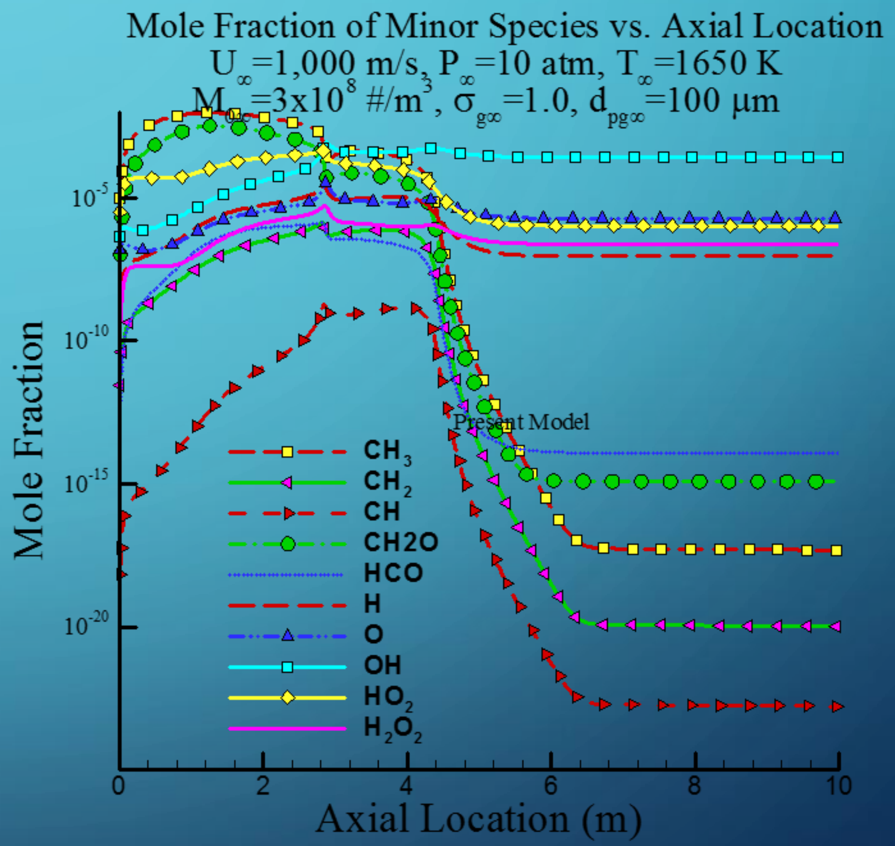
Reaction Mechanism:

- Methane/Oxygen
- 58 Step
- 17 Species
- Bilger and Starner (1990)

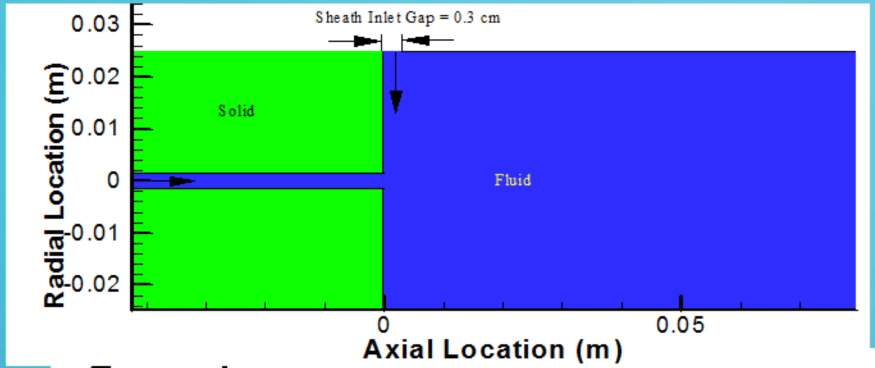


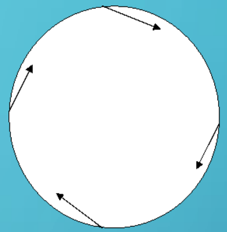
DROPLET COMBUSTION IN A SHOCK WAVE



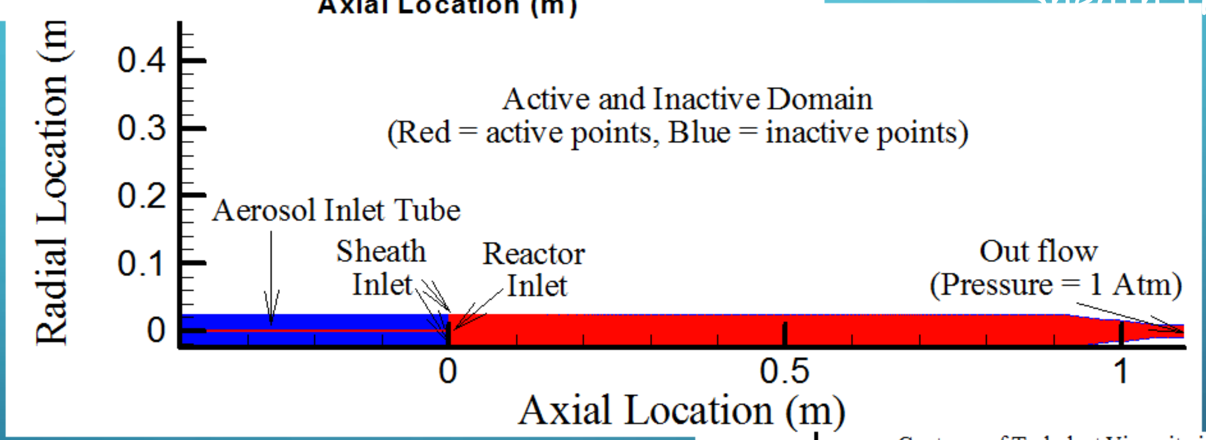


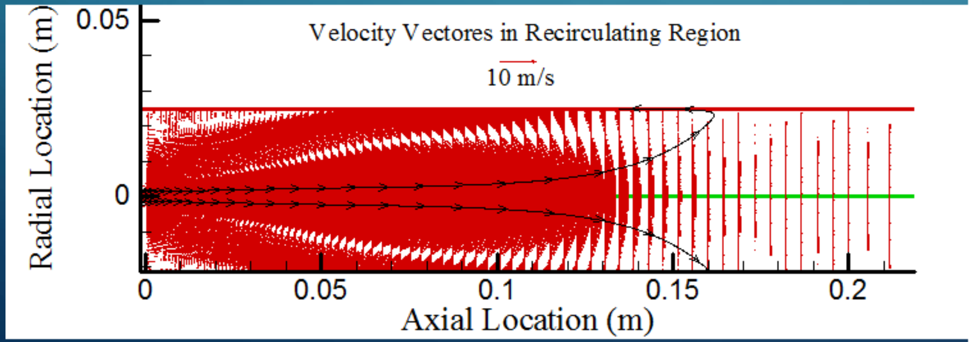
PARTICLE TRANSPORT AND DEPOSITION IN A NANOMATERIAL SYNTHESIS REACTOR

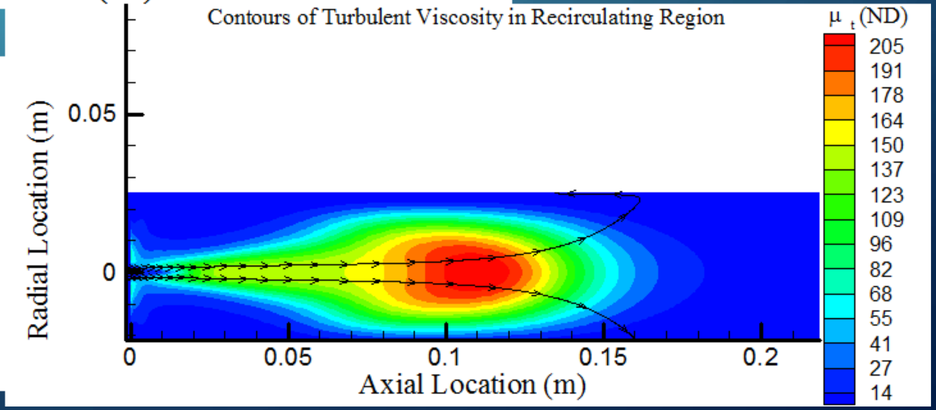




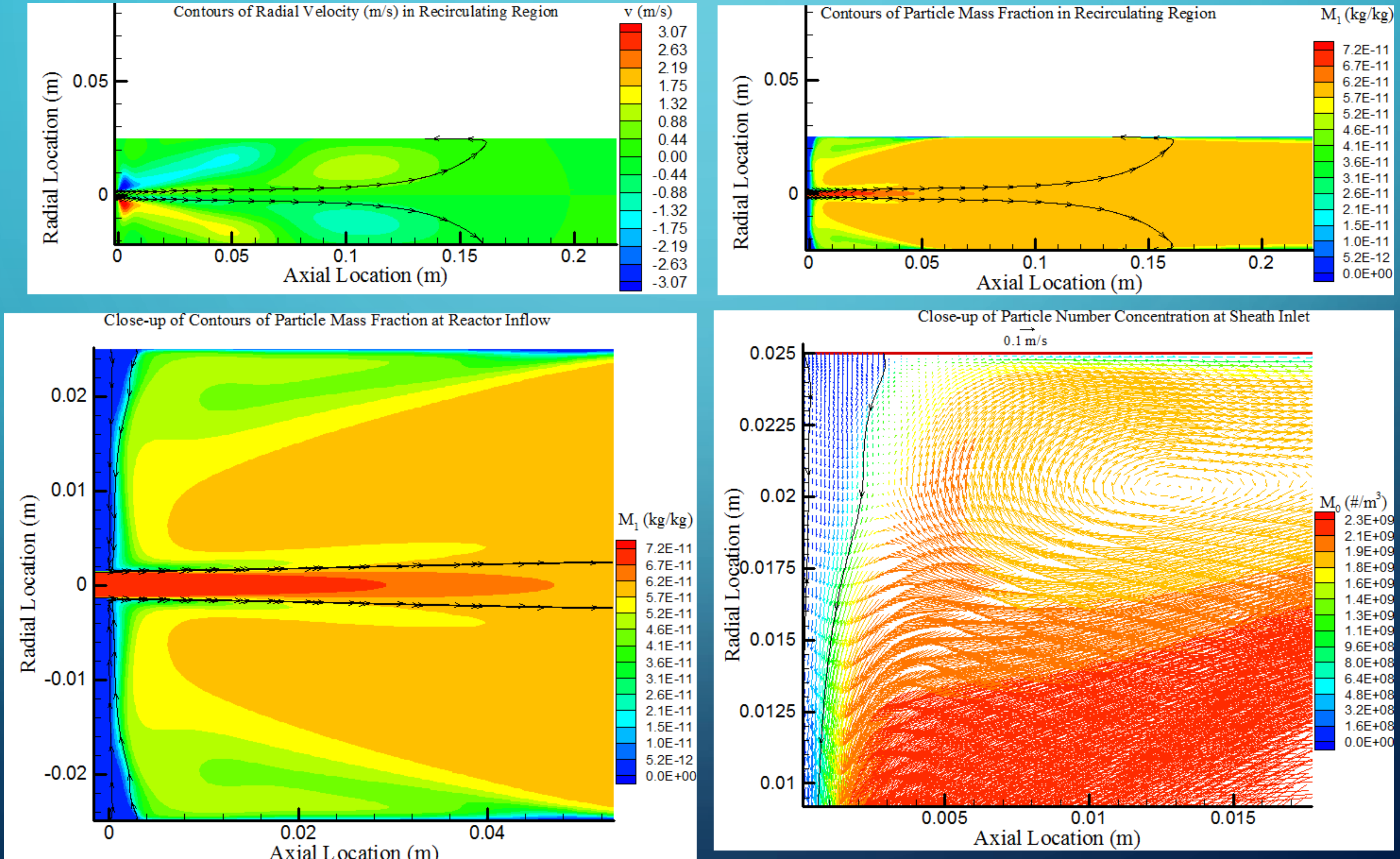
Sheath Inlet Radial Swirl







PARTICLE TRANSPORT AND DEPOSITION IN A NANOMATERIAL SYNTHESIS REACTOR



STRENGTH OF THE "TBD" TOKEN CORE ALGORITHM

- A general RNS based CFD code for aerosol transport and dynamics has been developed
  - Applicable over a wide range of particle sizes from nm to 100 mm (High diffusion to high inertia)
  - Applicable over a wide range of Reynolds and Mach numbers
  - Applicable for strong coupling between phases
  - Applicable to arbitrary geometries in one, two and three dimensions
  - Includes a wide range of aerosol transport and dynamics mechanisms coupled with gas phase and surface chemistry
  - It is efficient and accurate
  - Fully validated

- Conclusion
  - Faster, more accurate, more flexible and powerful computer modelling software, proven, in the real world.
  - Unless you are building advanced things, much of the above text was probably gibberish to you. If you didn't understand it, you'll probably enjoy the easier to understand token/utility/network whitepaper when it's available. It will cover all the cool Cryptocurrency token things ☺
  - https: //discord.gg/gvyFnKu